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FINAL REPORT

OPERATOR PERFORMANCE IN UNDERSEA MANIPULATOR SYSTEMS: STUDIES OF CONTROL PERFORMANCE WITH VISUAL FORCE FEEDBACK

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W. R. Bertsche
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January 1977

TECHNICAL REPORT

Prepared for the Office of Naval Research, Engineering Psychology Programs, Code 455 under Contract N00014-74-C-0179; NR 196-131.

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Approved for Distribution *Earl E. Hays*
Earl E. Hays, Chairman
Department of Ocean Engineering

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ABSTRACT

The major objective of this research was to identify and evaluate selected design variables in undersea manipulators with force feedback capability. A detailed survey of design variables and system dynamics was made in order to classify all variables and select those most critical to the design of the operator interface. An experimental manipulator with bilateral kinesthetic force feedback and visual-display force feedback was tested and the system's dynamic response capabilities were documented. A series of experimental tasks were performed by six subjects which indicated the relative advantage of manipulator systems with force control capability. Data collection equipments were designed and assembled which recorded forces and moments applied by the manipulator arm to the work surface during the execution of experimental tasks.

The two systems tested included a highly compliant unilateral position control manipulator and a similar system fitted with a visual display indicating forces applied by the slave manipulator arm. Results indicated visual displays allowed tasks to be performed with a significantly lower applied force. Visual displays aided in control of the manipulator's motion when the manipulator's motion was mechanically restricted. Visual displays aided in the control of the vector force along the line of sight of the observer. Utilization of visual displays required the operator to time share his visual patterns and resulted in generally longer task times. Both systems demonstrated an ability to control forces applied to the work surface, facilitating the execution of close tolerance and delicate work.

ACKNOWLEDGEMENTS

The authors extend their appreciation to Mr. Gerald Malecki and Dr. Martin Tolcott of the Office on Naval Research for their counsel in the conduct of this research program.

Recognition and appreciation is also extended to the various sections within the Woods Hole Oceanographic Institution for their patience and expertise in preparing this report. Ms. Nancy Wildes and Judith DeSanti for typing, and Frank Medeiros, Rene Halle, and Ron Williams for their excellent photographs. Special thanks is also extended to Edna Coneybear, Ruth Davis, Mike Mello and Fran Dunlap for their persistent effort in preparing the numerous charts and graphs used in the text of this report.

SECTION 1

DISCUSSION OF THE PROBLEM AND GENERAL APPROACH

1.1 INTRODUCTION

This research effort was performed to define and demonstrate through a program of experimental testing, the relationship between operator performance and selected design variables of the man-machine interface as found in force feedback manipulator systems. The performance data compiled during this effort contributes to the research literature concerned with the relationships between system dynamics and operator performance. The manipulator systems which are the subject of this research are generally high payload systems, typically deployed on manned submersibles or unmanned, remotely controlled, undersea work platforms. Mission requirements of these systems include underwater rescue, salvage, construction and research.

The present research effort in force feedback systems follows earlier efforts performed in the evaluation of the man-machine interfaces for rate and unilateral manipulators. These efforts included both laboratory and at-sea testing and were essentially completed in 1972 (Pesch, 1972 B). Results of these experiments and others (Flatau 1972, Vertut 1973, Nevins 1973, Groome 1972, Brodie 1973) indicated that further gains in operator performance might be achieved by the provision of a force feedback capability. Reasons sited included:

- Addition of a sensory channel to provide redundancy to visual feedback with degraded visibility
- Reduction of damage to the work surface, manipulator tools and slave manipulator arm.

- Increased task capability with regard to close tolerance and delicate work situations.
- Increased task capability in following surfaces or contours.
- Detection and control of forces imparted to the manipulator arm by motion of either the submersible, work platform or work surface itself.
- Elimination of the need for the design of special non-destructive tools and self alignment features.

The present research program was initiated to substantiate and quantify these gains on an applied experimental basis. The experimental design and performance measures utilized were carefully selected in order that a multidimensional quantitative evaluation of force feedback capability could be made. The results are significant from the point of view of both the demonstration of a performance measurement technique for force feedback systems and the indication of the relative performance improvement with the provisions of visual force feedback information. This report described the results of an experimental evaluation of a baseline unilateral manipulator system with and without visual force feedback displays.

1.2 INITIAL PROJECT RESEARCH

Prior to the execution of the experiments reported here, this research program concentrated on the identification and selection of critical force feedback design variables. An experimental bilateral underwater manipulator system (Bertsche 1975A) was used in various test configurations for the exploration of the complex relationships present across force feedback variables. A report was prepared (Bertsche 1975B) which identified major system design variables and defined engineering test methods for the quantification of these variables. In a summary report (Bertsche 1976) a selection was made of the most critical

variables affecting the man-machine interface of undersea force feedback manipulator systems. This current effort is directed toward the evaluation of one of the critical variables identified: visual force feedback. Selection of visual force feedback over a bilateral system was made for the following reasons:

- Implementation of such a system for actual deployment is feasible and practical at the present time.
- The costs of implementation of an operational system are far less, (perhaps by an order of 5 to 10.), than those associated with complex bilateral systems or computer controlled systems.
- Much of the developmental research associated with the force sensing, transformation, and display is complete, Hill (1974), Groome (1972), Flatau (1972, 1973), Nevins (1973).
- It was possible to simulate a prototype system on the current experimental manipulator system with a high degree of accuracy.

SECTION 2

DERIVATION OF FORCE CONTROL PERFORMANCE MEASURES

An overview of previous manipulator testing programs led to the conclusion that task completion time, force application and, perhaps, power consumption would provide adequate measures of performance with force feedback systems. Where a fair number of performance tests utilizing time and power consumption are documented, few report actual measurement of differences in force application. It was necessary, therefore, to determine the requirements of a force measurement system prior to initiating the testing program. These requirements were developed by first determining the typical force control behavior necessary for undersea work and then creating a measurement system which could uniquely indicate relative differences in force control behavior as a function of operator control configurations.

Six typical underwater tasks were evaluated to determine the force control requirements. The six tasks included:

- Drilling/tool use
- Hooking/engaging
- Shackel makeup
- Contour or surface following
- Assemble parts
- Compensate for vehicle drift

The following conclusions were reached:

1. The operator's performance may be analyzed through measurement of his ability to control the force output of the slave manipulator arm.

2. The operator is not required to judge the absolute value of forces he applies during work and this ability need not be measured.

3. The operator must sense and minimize forces imposed on the slave arm by phenomenon not under his immediate control, e.g. vehicle drift, shifting work surface, etc. A measurement of the force output would indicate such ability.

4. There appears to be a division of task requirements between linear control and rotational control. Linear control requires linear positioning movements and vector load control. Rotational control requires rotational movements, rotational torque control, and control of grasp. Each of these control behaviors should be measured independently.

5. Common linear force control behavior elements identified in the task analysis included:

a) apply/limit force along vector
b) make contact
c) withdraw or insert with least resistance
d) maintain/limit force on contour or surface
e) control force on moving object

6. Common rotational torque control behavior elements identified in the task analysis included:

a) sense touching object
b) sense torque and loading moments and control or align for normal to surface
c) orient for least resistance
d) control grasp force
e) control force of contact
f) control force on moving object

7. Spatial control and force control behaviors may be tested independently.

Considering conclusions 1, 2 and 3, it appears that recording the forces the slave arm applies to the work surface will be sufficient for the characterization of an operator's force control behavior. Conclusions 4, 5 and 6 support a requirement for the independent recording of both vector forces and rotational torques. Recording of an orthogonal set of three force vectors and three rotational torques would, therefore, uniquely document all force control behaviors. Conclusions 4, 5 and 6 also imply that the majority of underwater work requiring force control, may be characterized by just a few basis control behaviors. Independently testing the operators ability in performing each of these elements should provide an indication of the operators overall ability to control force.

For the experiment documented in this report, the resultant force applied by the slave manipulator arm to the work surface was represented by an orthogonal set of three force vectors oriented in spherical coordinates. These included the forces in the azimuth, elevation and normal directions relative to the intersection of the shoulder rotate and shoulder pivot axes. Two orthogonal wrist torques were recorded as representative of rotational torque applied to the work surface. (The third orthogonal torque was not available for recording on the experimental manipulator system). In order to provide one value representative of force control behavior, the absolute values of each force vector and rotational torque were integrated over the period of task performance. Dividing this integral by a time period provided a measure of the average absolute value of applied force and torque for each behavior element. Appendix A, Section A-4, describes the details of the data collection techniques used for this experiment.

SECTION 3

EXPERIMENTAL APPROACH

This section details our approach to operator performance evaluation of force control with underwater manipulator systems. The facilities, experimental designs, subjects, data collection requirements and experimental tasks are described. Our approach was directed towards the replication of realistic underwater manipulator work and working conditions. Our intent was to investigate a range of force control behavior elements identified within selected work tasks.

3.1 GENERAL DESCRIPTION OF TESTING FACILITY

The test facility consisted of an operator's station, slave manipulator, work stand, and data collection station. A spherical shell simulated an operator's station within a typical submersible with a forward viewport. The slave manipulator was located directly in front of this viewport. The operator assumed the conventional "Moslem at Prayer" position for a clear view of the slave manipulator and work area, Figures 3.1. The master control harness was suspended inside the shell, allowing ample room for the operator to manipulate the harness. Also, located inside the shell was a shoulder rotate offset adjustment. This control was designed to allow the operator to rotate the slave manipulator up to $\pm$ 30° while holding the master harness stationary, thus, allowing the operator a greater amount of comfort in awkward working positions. Attached directly in front of the viewport to the outside of the shell was a panel of force meters. The panel of force meters displayed for the operator were: grip, elevation, azimuth, and normal forces applied by the slave manipulator to the work surface.

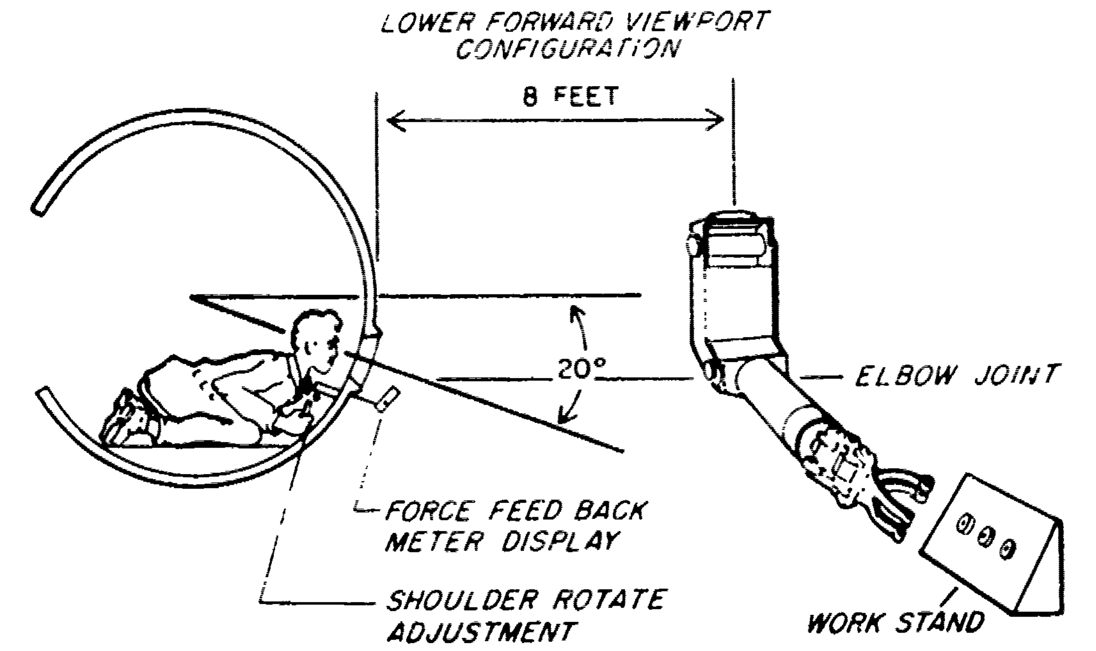


FIGURE 3.1.1 SUBMERSIBLE VIEWPORT MOCKUP, SECTION VIEW

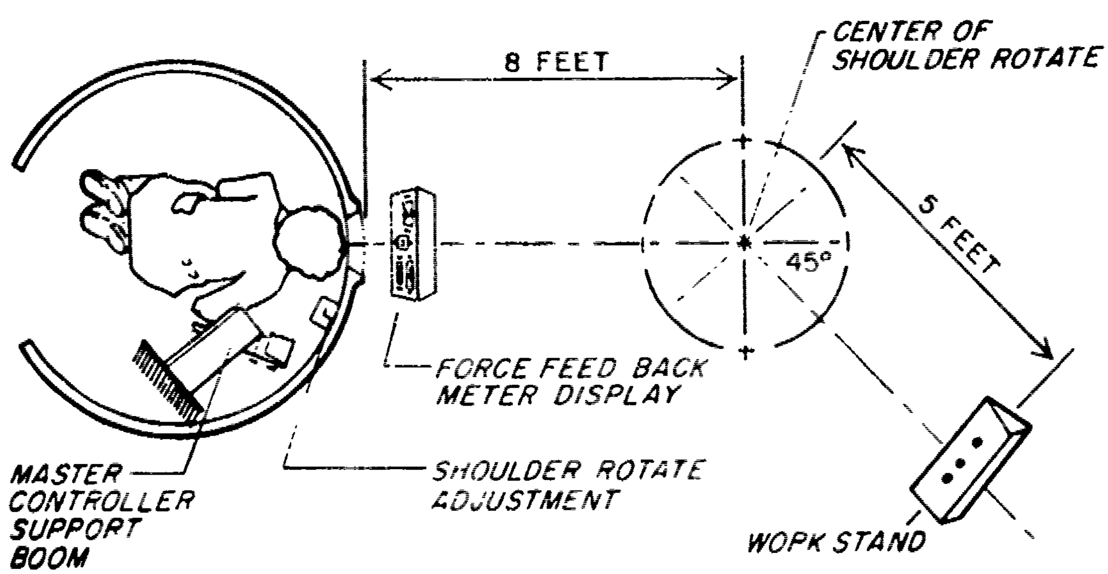


FIGURE 3.1.2 MANIPULATOR MOCK UP, PLAN VIEW

<u>FIGURE 3.1</u> ARRANGEMENT OF EXPERIMENTAL FACILITIES

A work stand was provided as a support for the apparatus used in various tasks. It consisted of a welded steel support with adjustable bolting studs. This allowed for interchange of work surfaces in the surface following core tube and drilling tasks. The stand was securely positioned to minimize variability in experimental conditions.

An observer's station was located to the right of the operator's shell. From this station, the observer had a clear view of the work area and could not be seen by the operator. The station included: a program sequencing switch, a data scan switch, a digital voltmeter and a writing surface. The hydraulic power plant was also controlled from this station.

The entire viewing area of the operator was enclosed by a canvas curtain backdrop to reduce visual distractions.

3.2 DESCRIPTION OF THE TEST MANIPULATOR SYSTEMS

Two manipulator configurations were evaluated according to this experimental test plan. The first system is by strict definition a unilateral position controlled manipulator system calibrated with unusually high compliance. It is termed the "baseline" configuration in order to identify it as a system uniquely different from the low compliance "position" systems previously utilized in manipulator testing programs (Pesch, 1972B). The second system is the baseline system with the addition of a visual force feedback display. It is important to realize that it is possible to control force output of the slave manipulator arm utilizing either of these systems.

Figure 3.2 indicates a schematic representation of the two configurations. Force sensing in these two systems is accomplished by a servo error technique. Readers interested in a detailed engineering description of these systems are referred to a previous report (Bertsche 1975A) and Appendix A of this report.

The baseline manipulator configuration consisted of a slave manipulator, a harness type master controller, and a visual force feedback meter panel. This master controller is utilized by the operator to control the position and forces applied by the slave manipulator. The meter panel indicated to the operator the magnitude and direction of the forces applied by the slave manipulator to the work surface.

3.2.1. Function and Description of the Slave Manipulator Arm

Position control of the slave manipulator was as follows: the slave manipulator moves to match deflections of the master controller. Forces applied by the slave manipulator are also controlled by the master controller. The forces applied to the work surface are proportional in magnitude and direction to the distance and direction the master harness is caused to "reach through" the work surface. That is, the further the master harness was extended once a surface was touched, the harder the slave manipulator arm would push on that surface: a one inch motion of the harness beyond the surface touched caused 15 lbs. of force to be applied to the work surface, and a two inch motion of the harness caused 30 lbs. of force and so on. Zero force was applied when the slave manipulator arm was "just touching" the surface. Such control of force was achieved by making the system highly compliant.* A rapid time response was maintained by utilizing special signal (see Appendix A, Section A.3) processing to offset the effects of compliance on system performance.

* Compliance: The distance the tip of the manipulator is deflected from no load to full load conditions (inches) divided by the load (pounds).

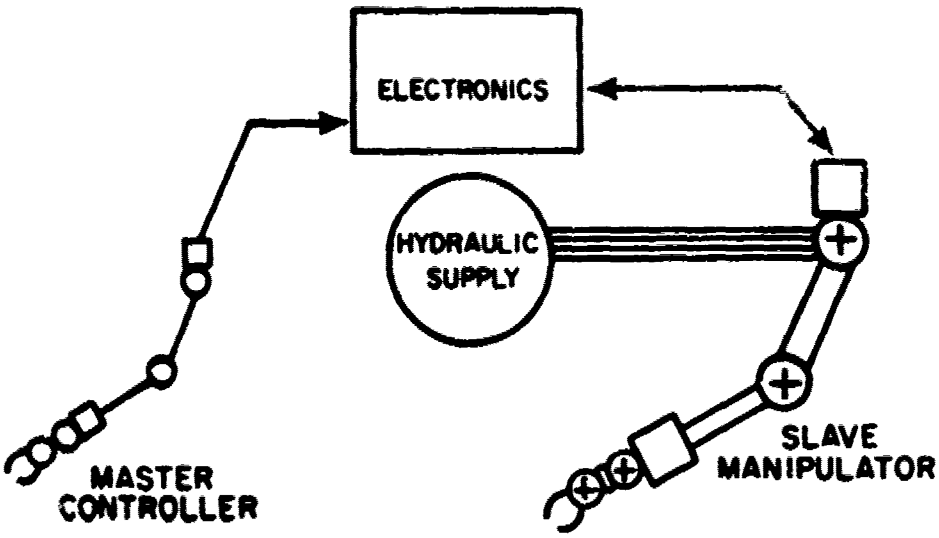


FIGURE 3.2.1 BASELINE CONFIGURATION

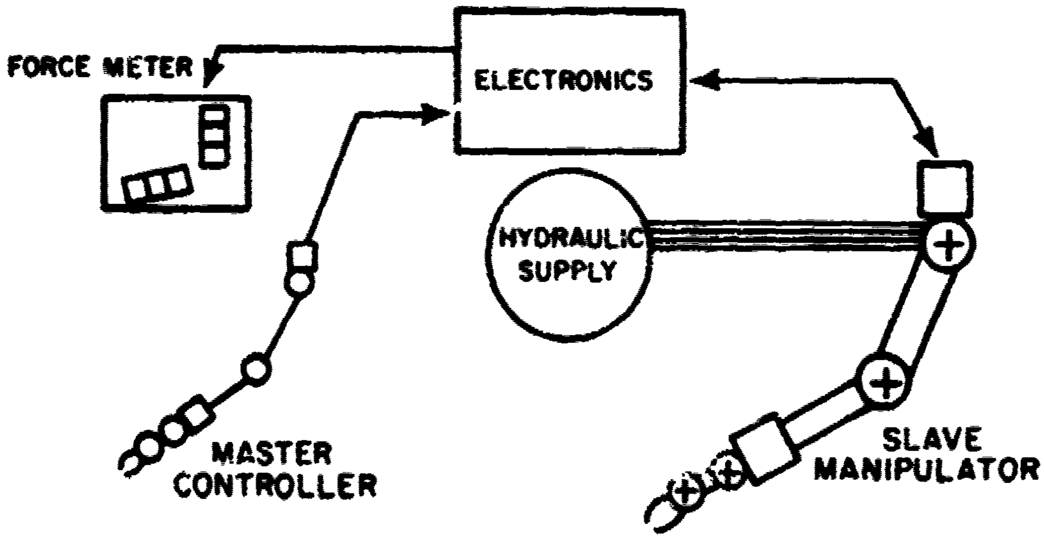


FIGURE 3.2.2 BASELINE WITH METERS CONFIGURATION

FIGURE 3.2 SCHEMATIC REPRESENTATION OF THE MANIPULATOR TEST CONFIGURATION

3.2.2 Functions and Description of the Master Controller

The master controller was of a harness type specifically designed for the space limitations of a submersible environment. The anthropomorphic joints of the harness replicate the joints of the slave manip[illegible]. The harness was suspended from a boom mount. The oper[illegible] arm was inserted through a fore arm cylinder into [illegible]ing hand and wrist assemblies which were full si[illegible]. The fore arm and upper arm sections shortened, as illustra[illegible]ed in Figure 3.4, allowing full reach within the confinement [illegible] submersible. Proper control of the manipulator was achiev[illegible]y moving the hand assembly in the direction desired.

3.2.3 Function and Description of the Visual Force Feedback Meter Display Panel.

The variable of interest in the experiment was the utilization or non-utilization of visual force feedback displays during the performance of a manipulator task. The force feedback display provided force information which indicated the magnitude and direction of the forces being applied by the manipulator arm to the work surface. The forces selected for display are the forces applied to the work surface in spherical coordinates. The forces form an orthogonal set of force vectors parallel to the tangents and normal of a sphere whose center is the intersection of the shoulder pivot and shoulder rotate axes. The three vector forces displayed were azimuth force, elevation and normal forces. The azimuth force was horizontal relative to the ground plane. The direction of these forces relative to the slave manipulator and the display as viewed by the operator are indicated in Figure 3.5.

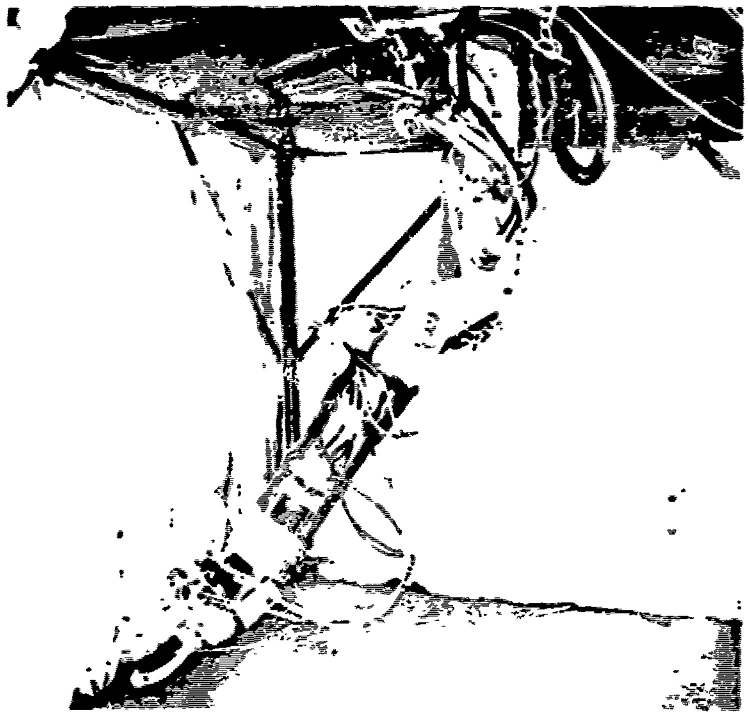


FIGURE 3.3.1 MANIPULATOR SLAVE ARM USED IN TEST PROGRAM

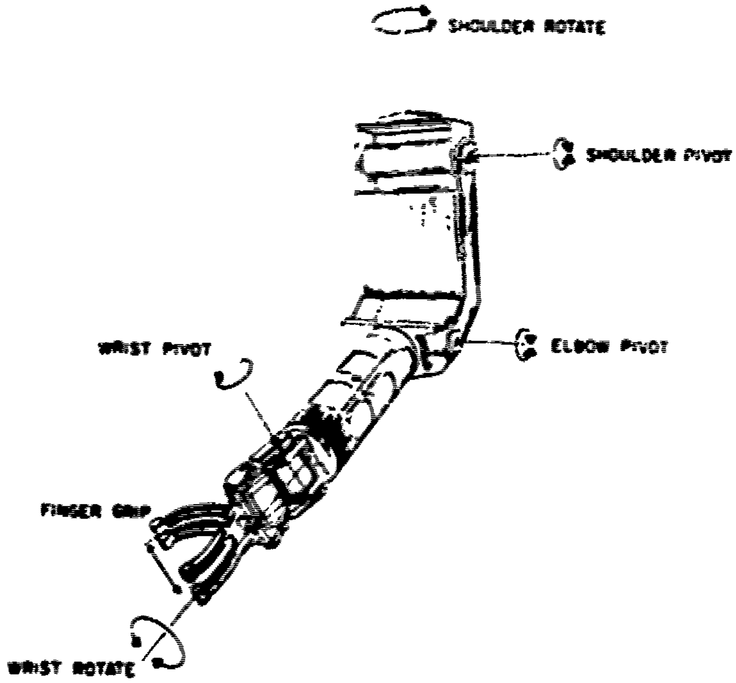


FIGURE 3.3.2 PICTORAL SKETCH ILLUSTRATING SIX DEGREES OF AVAILABLE MOTION

FIGURE 3.3 SIX DEGREE FREEDOM MANIPULATOR SLAVE ARM

The baseline slave manipulator was configured as shown in Figure 3.3. There were six degrees of freedom. The slave manipulator arm was 6.5 feet in length fully extended, had a lifting payload of 200 lbs. and a compliance of .25 in./lb. The following general properties were measured for all joints except shoulder rotate:

- Backlash (hand): 5 lbs.
- Backlash (other joints): 15-20 lbs.
- Rise time (each joint): .4 - .6 sec.
- Settling time (each joint): 1.2 - 1.5 sec.
- Slew rate (each joint): 60 deg./sec.

The following properties were recorded for the shoulder rotate joint. The reader may note that the backlash of this joint was noticeably higher than the other joints. Higher loop gains were also required to maintain good position control and subsequently reduced the horizontal compliance to .02 in./lb. The horizontal payload principally controlled by this joint was 500 lbs.

- Backlash: 40 lbs.
- Rise time: 1 sec.
- Settling time: 2 sec.
- Slew rate: 45 deg./sec.

Compliance, payload, and backlash are noticeably different for the shoulder rotate joint. Hardware limitations had prevented balancing such properties across the entire system. These differences may have contributed to minor variations in the experimental results which indicated higher azimuth forces were applied while performing certain of the experimental tasks. These effects are discussed in detail in Section 4.

Forces applied by the manipulator were indicated on the individual meters. The meters deflected in the direction the force was applied, providing a natural control/display motion relationship for the operator. Application of a force in the direction of an arrow required moving the hand of the control harness in the direction of the arrow. Forces were reduced to zero by moving the hand back toward zero.

Maximum scale deflections for the meter display were selected to provide an adequate range of force indication necessary for the performance of the tasks anticipated. The slave manipulator, however, was capable of applying forces in excess of those indicated. Table 3.1 indicates the maximum display scales selected and the ultimate force capability of the slave manipulator in these respective directions.

3.3 SUBJECTS

The subject pool in this experiment consisted of six subjects, all of whom had little or no previous experience in operating manipulators. Major factors which led to the choice of naive subjects included: (1) the selection of an unbiased subject group (2) the control of learning in this experimental design. Our experience in previous experiments indicated that naive subjects were able to rapidly master the use of harness type controller (Pesch 1372A). We provided an extensive training program for each subject, and thus, planned to minimize the learning effects in the experiment. Experimental data support the success of this training program.

3.4 EXPERIMENTAL DESIGN

In any experiment, an attempt must be made to reduce the effects of uncontrollable variables which may have a consequence on the internal validity of the results. The variance in the

TABLE 3.1 METER CALIBRATION AND PAYLOAD FORCES OF THE SLAVE MANIPULATOR RELATIVE TO THE WORK SURFACE

FORCE	METER RANGE	SLAVE MANIPULATOR'S FORCE GENERATING CAPABILITY
AZIMUTH	± 200 lb.	± 540 lb.
ELEVATION	± 200 lb.	± 210 lb.
NORMAL	± 200 lb.	± 370 lb.
GRIP	± 25 lb.	± 27 lb.
WRIST PIVOT	NO METER	± 120 lb.-ft.
WRIST ROTATE	NO METER	± 110 lb.-ft.

FIGURE 3.4.1 UNILATERAL POSITION CONTROLLER

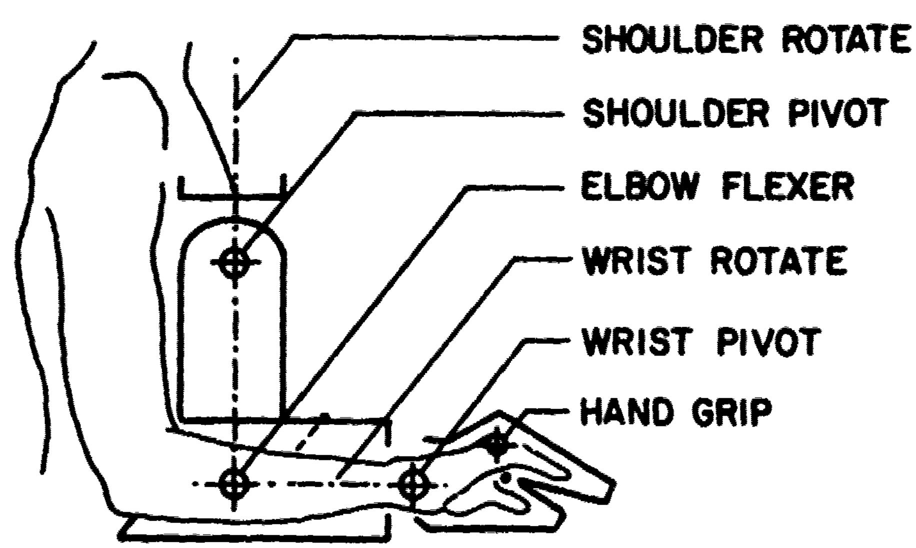


FIGURE 3.4.2 PICTORAL SKETCH ILLUSTRATING SIZE AND DEGREES OF FREEDOM OF MASTER CONTROLLER

FIGURE 3.4 SIX DEGREE FREEDOM MASTER CONTROLLER

data, due to such variables as noise distractions, and lighting may lead to inaccurate inferences and conclusions concerning the effects of the independent variables being tested. Given the fact that the major sources of secondary variation do not evenly contribute to a particular experiment, a design was chosen that would best control those sources considered to have the most influencing effect on the dependent variables relevant to this experiment. (In our case, the primary dependent variables included force, and time.) The experimental design employed in this test was the basic 2 x 2 Latin Square. This design could effectively reduce experimental error through a counter-balancing of a secondary variation across conditions. The use of six subjects in the experiment allowed three replications of the square.

3.5 DATA COLLECTION

3.5.1 Recording Station

The test observer was stationed next to the operator's shell. He controlled the start and ending of all tasks by verbal commands to the subjects. He controlled the data collection circuits by progressively switching a six position program sequencing switch as particular portions of each task were completed. At the completion of the entire task, he recorded data and reset the recording circuits. One test observer was utilized during the total experiment.

Data were collected on an iterative analog computer during each task. Voltages representative of the performance were recorded by the observer. These voltages were later processed by a digital computer to formulate the actual performance measures reported. (See Appendix A, Section A.4)

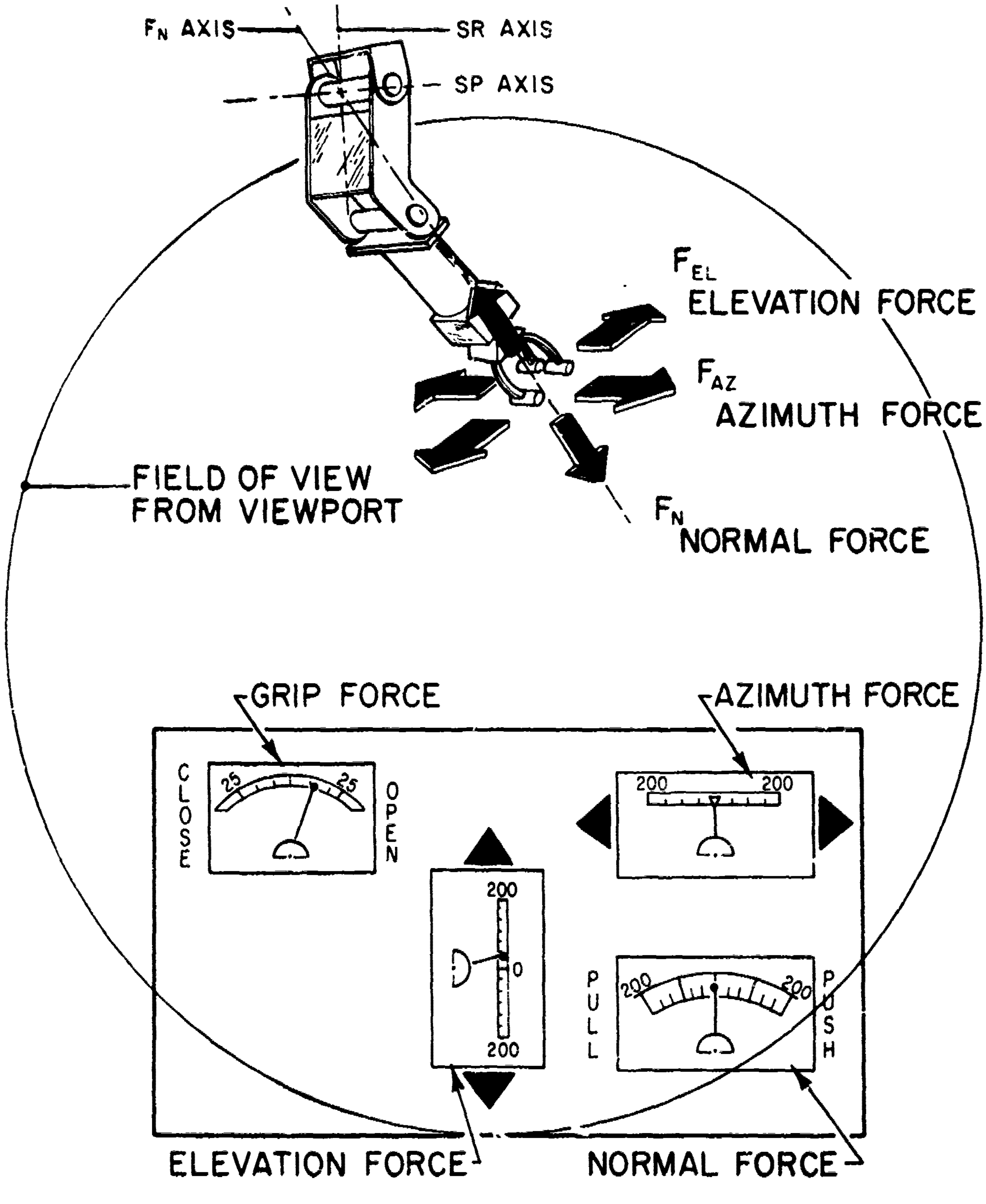


FIGURE 3.5 TYPICAL VIEW OF FORCE FEEDBACK METER DISPLAY AND WORKING POSITION OF MANIPULATOR ARM

3.5.2 Time and Average Force Measurement

Time and average applied force measures were used to evaluate the operator's perfo nce of the various tasks. The time measure was indicative of the duration of each task element. The average applied force measure was the average of the absolute value of the force applied during selected task elements. Six average forces or moments were recorded simultaneously: azimuth, elevation, normal, grip forces, wrist pivot and wrist rotate moments. A resultant force vector representative of the azimuth, elevation and normal force vectors was also calculated.

3.5.3. Correction for Acceleration Forces and Residual Dead Weight Signals

In order to provide more accurate values of average applied forces, acceleration forces and fixed bias signals had to be isolated and subtracted from the data. These correction data were generated by simulating movements in each task, without actually applying force to tools or apparatus. A total of ten trials were recorded for each task. Averages for each force component were calculated and subtracted from corresponding values in all experimental data.

3.6 OVERALL TASKS AND SUBTASKS

This section briefly describes the tasks performed in the experiment. The order in which the tasks were performed was held constant throughout the experiment. The tasks and order of performance were as follows:

1. Sample Retrieval
2. Surface following
3. Core Tube at 45°
4. Core Tube at vertical
5. Drilling

3.6.1 Sample Retrieval Task

This task simulates retrieval of delicate samples or instruments from the ocean floor. It required the operator to securely grasp a hollow aluminum block, move it to a container, and drop it in. The block was positioned on a platform located directly in front of the shell. The container was located on the work stand, the opening of which measured 12" x 12". There existed a difficulty factor due to the restriction of depth perception to two planes while grasping the block which was placed directly in line with the viewpor and shoulder rotate axis.

The object of the task was to grasp the block with minimum grip force and maintain that force while moving it to the container. The operator had to determine the minimum grip force required to hold the block by repeatedly lifting and dropping the block, and noticing the harness position that would successfully hold it. The critical control function fo this task was holding the initial minimum grip force constant during movement to the container. Figure 3.6 illustrates the various elements of the task.

Time, and average forces were recorded for two behavior elements or subtasks identified within this task:

- Control grasp force
- Control grasp force while moving

3.6.2 Surface Following Task

This task was designed to simulate the use of an underwater torch to cut a closed circula. path eight inches in diameter. The surface to be cut was the face of a 20" x 20" x [illegible]" plywood board placed normal to the F_N axis of the manipulator arm.

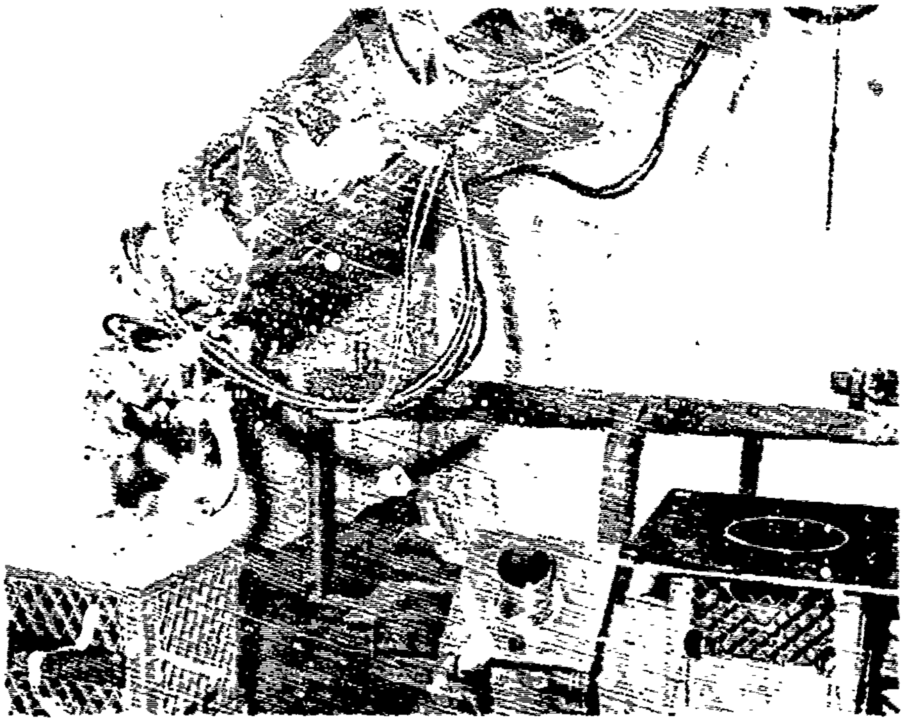


FIGURE 3.6.1 GRASPING THE OBJECT

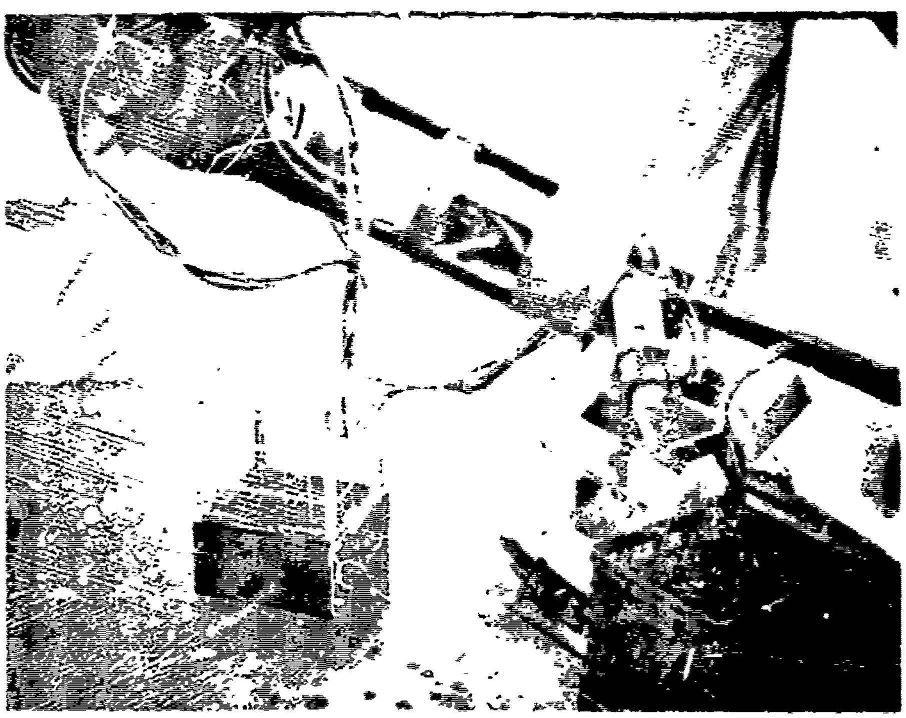


FIGURE 3.6.2 TRANSPORTING OBJECT TO CONTAINER

FIGURE 3.6 CONTROL ELEMENTS OF THE SAMPLE RETRIEVAL TASK

The plywood was painted black to provide the operator with a distinct visual trace of the cut path. A router was used to simulate a cutting torch. The router was provided with a T-bar handle which allowed the tool to be rigidly grasped by the manipulator claw. The router had been modified with special shock absorbers to prevent it from becoming damaged, consequently, a force applied to the surface was partially absorbed by the tool. The operator was, therefore, offered a visual cue to the magnitude of force applied by watching the amount of compression of the shock absorbers on the router. The router was equipped with two large roller bearings at contact points to insure free movement along the surface of the wood.

The operator was required to start the contour at the top of a circle chalked onto the wood. Motion was in a counter-clockwise direction, following the outline of the circle. Figure 3.7 illustrated the various elements of the task.

The critical control functions included the following:

A. Initial as well as continual alignment with the surface on the board. The tool had to remain perpendicular to the surface in order for a cut to be made.

B. Alignment of router center and the circle outline was required.

C. Control of force with which the tool was pressed on the surface. Excessive force could damage the tool or cause the tool to become dislodged from the claw.

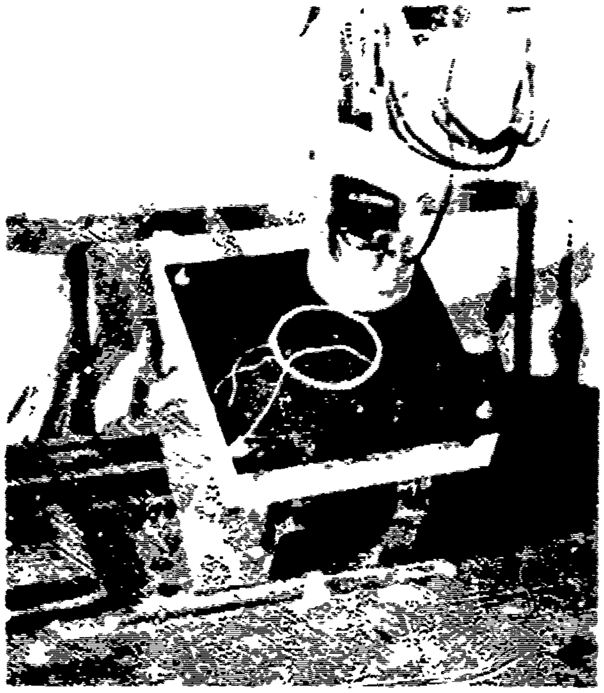


FIGURE 3.7.1 ALIGNMENT OF CUTTER TO WORKING SURFACE

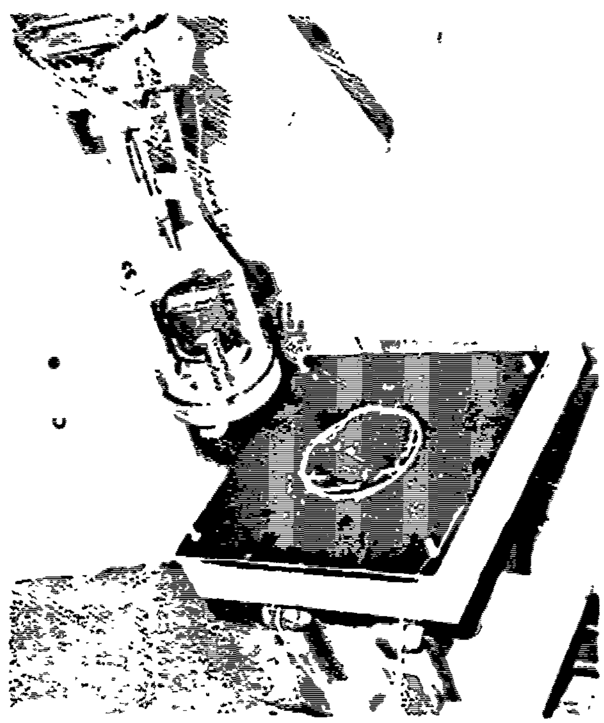


FIGURE 3.7.2 CUTTING SURFACE ALONG CIRCLE

FIGURE 3.7 CONTROL ELEMENTS OF THE SURFACE FOLLOWING TASK

This was an extremely difficult task to perform proficiently. It required a good sense of perception, and a great deal of coordination on the part of the operator. Time, average forces and accuracy were recorded for two behavior elements of subtasks identified within this task.

- Maintain/limit force on contour or surface (pulling motion)
- Maintain/limit force on contour or surface (pushing motion)

3.6.3 Core Tube Task at 45°

This task required the placement and withdrawal of a simulated bottom sediment core tube into and out of a close tolerance sheathe. The core tube diameter was 3", its length was 14". The sheathe opening diameter was 3 1/16", its length was also 14". This is a typical task presently performed by the submersible ALVIN. The difficulty of the task was compounded by the fact that the core tube was rigidly held in the claw. The core tube was marked with black paint around its upper section to indicate when the tube had been fully inserted. The sheathe was fastened to the work stand on an angle of 45°, i.e., parallel to the F_N axes of the manipulator arm. Figure 3.8 illustrates the control elements of this task.

The task consisted of three basic control functions. These included alignment of the tube with the sheath opening, insertion of the tube, and withdrawal of the tube. The critical functions of the task were the following:

A. Proper wrist alignment. The wrist joints had to be continually aligned parallel to the angle of the sheathe in order to prevent excessive binding forces.

B. Coordination of motion in a straight line. This required coordination of the shoulder, elbow, and wrist pivot joints.

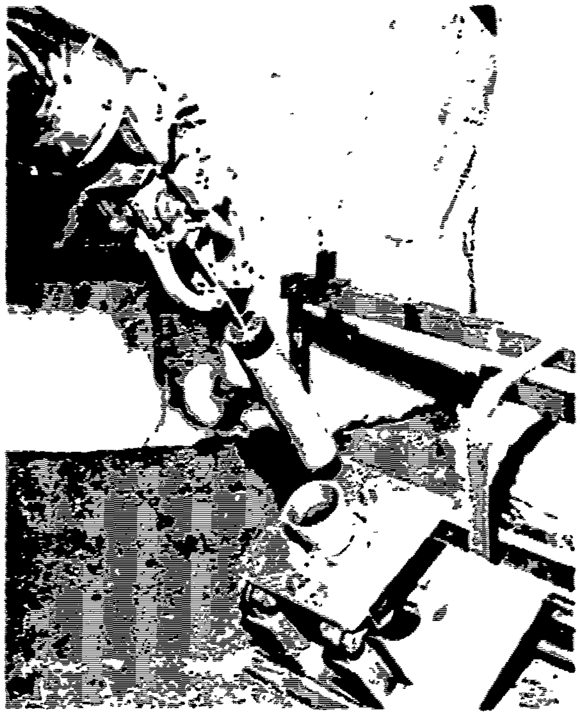


FIGURE 3.8.1 ALIGNMENT OF CORE TUBE WITH SHEATHE

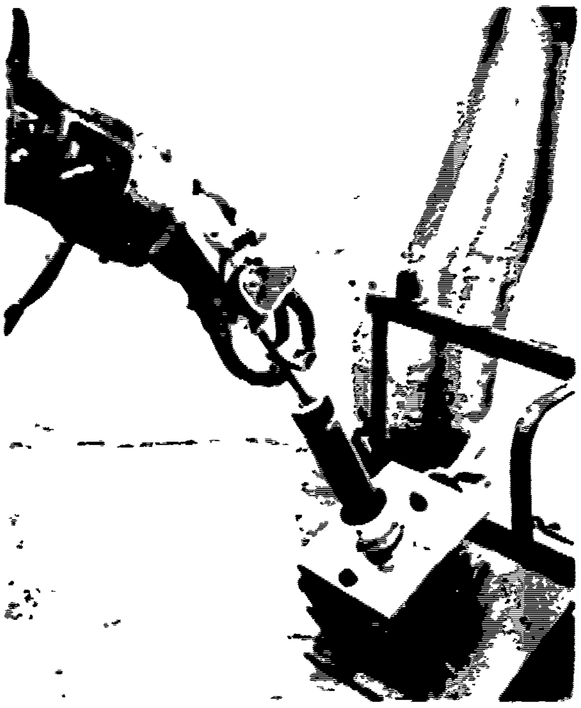


FIGURE 3.8.2 INSERTION AND WITHDRAWAL OF CORE TUBE

FIGURE 3.8 CONTROL ELEMENTS OF THE CORE TUBE TASK AT 45°

Time, and average forces were recorded for two behavior elements identified within this task.

- Insert with least resistance
- Withdraw with least resistance

3.6.4 Core Tube Task Vertical

This task is similar to the core tube task previously described with the exception that the angle of the sheathe is now vertical, (i.e., perpendicular to the floor). The critical functions remain the same as those listed in the task above. Interpretation of the meter display relative to the task is more difficult since motion was not among a force vector displayed on the meter panel. Time, and average forces were recorded for similar behavior elements identified above.

3.6.5 Drilling Task

This task required the operator to drill a ½" hole in a 12" x 12" x ½" aluminum plate supported normal to the F_N axis. The drill was fastened to the manipulator arm and required no operator control of grip force.

The operator was required to align the drill bit with a black ½" diameter dot marked on the plate, and commence drilling. Once drilling had begun, the drill was held in a steady position until the hole passed completely through the plate. Having accomplished this, the operator would insert the bit half its length then withdraw the drill bit from the hole. Figure 3.9 illustrates the control elements of this task.

The critical control functions of the task were the following:

A. Alignment of the drill bit with the black mark on the plate. It was crucial that the drill bit was

FIGURE 3.9.1 ALIGNMENT OF DRILL WITH ALUMINUM PLATE

FIGURE 3.9.2 DRILLING HOLE IN ALUMINUM PLATE

FIGURE 3.9 CONTROL ELEMENTS OF THE DRILLING TASK

aligned perpendicular to the surface of the plate in order to prevent slippage of the bit from the mark. There were no prick holes on the plate to hold the bit in place.

B. Directional force control in drilling. The operator was required to provide a straight line of force both to insure accuracy and to prevent the drill bit from binding or breaking.

C. Directional force control in withdrawal. The direction of the force was reversed; straight line motion was required to minimize forces.

Time, and average forces were recorded for two behavior elements or subtasks identified within this task.

- Apply/limit a force vector
- Withdraw with least resistance.

SECTION 4

RESULTS AND DISCUSSION

This section presents the results of the experiment and an interpretation of the findings. A comparison of performance is made between a baseline system and a baseline system with meters. Statistical support noted for the findings may be found in Appendix B. The statistics tests applied were factorial analysis of variance involving three factors: subjects, systems and trials.

4.1 LEARNING

There always exists the possibility that the variability due to learning will affect the results of an experiment. A Latin Square design was used to reduce this possibility. In addition, each subject received an equal amount of training on the manipulator to become familiarized with the fundamental aspects of manipulator control. Specific training was also given for each task.

The resultant force vector for elevation, azimuth, and normal forces is plotted as an overall learning curve in Figure 4.1 for all conditions, all subjects, all tasks (excluding sample retrieval), and all trials. This curve shows that, although some variability in performance existed, the subject population did not undergo a learning process during the data collection period that would significantly affect the results. The variability evident in these data may be attributed to statistical differences in subjects and tasks.

It is worth noting that a similar low learning effect was observed on unilateral systems while utilizing a similar harness (Pesch, 1972A). These data may indicate that the training sessions were highly effective and that learning probably occurred during these short training periods.

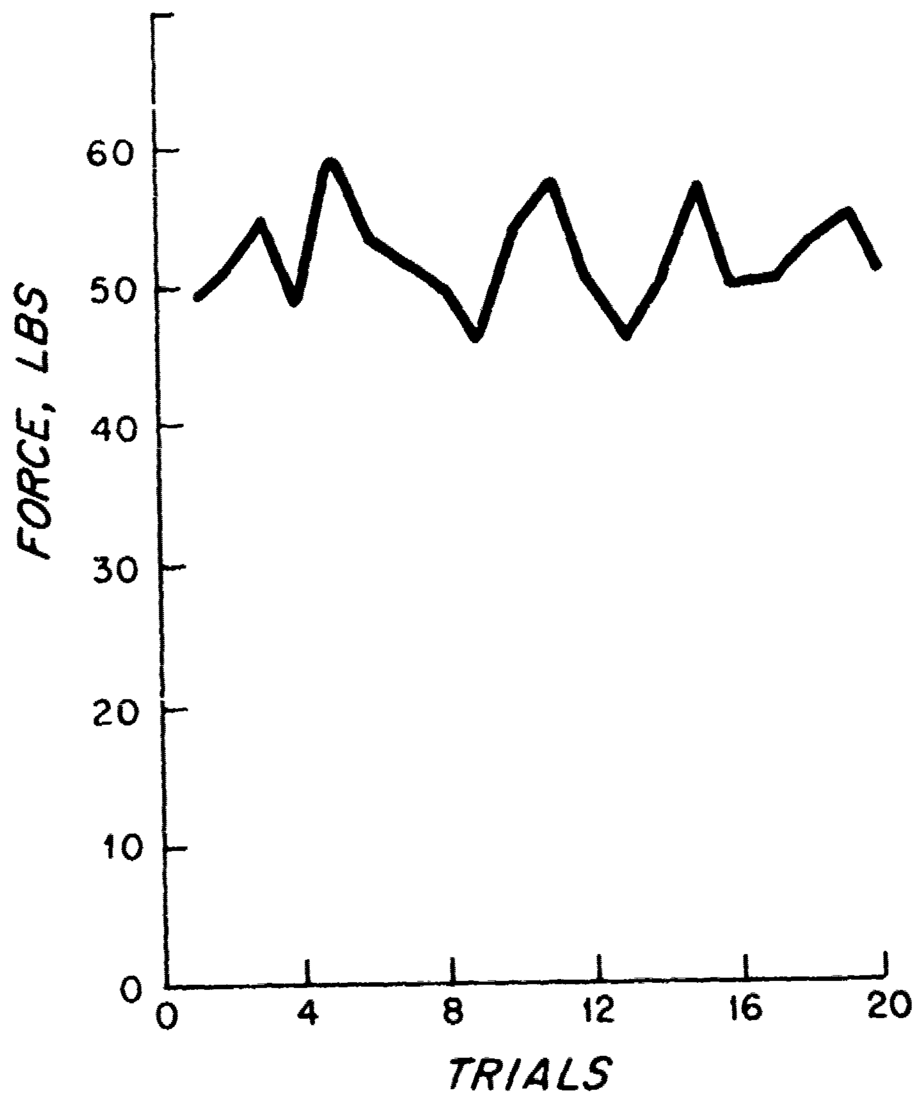


FIGURE 4.1 AVERAGE OVERALL LEARNING CURVE FOR RESULTANT FORCES FOR ALL CONDITIONS, SUBJECTS, TASKS AND TRIALS

4.2 PERFORMANCE EVALUATION OF CORE TUBE TASK AT 45°

This task required the placement and removal of a bottom sediment core tube into and from a close tolerance sheathe that had been skewed to an angle of 45°. Descriptive task forces were recorded during core tube insertion and withdrawal behavior elements. The operator's objective was to minimize force in all directions while coordinating straignt insert and withdrawal motions.

4.2.1 Force Control Behavior Recorded During Core Tube Task at 45°

Average amounts of force exerted in the three component vectors of applied force were significantly reduced with the addition of feedback meters. Figures 4.2.1 and 4.2.3 show respective average elevation and normal forces for each task element. Lower forces were recorded for the baseline-with meters system during both the insertion and withdrawal elements, with the latter element statistically significantly different at the .05 level for both elevation and push-pull forces. Figure 4.2.2 shows differences in azimuth forces between systems, statistically supportable at the .01 level durinc both task elements. Operators exerted less force in the elevational direction than in the other two directions. This may be the result of a visual advantage in perspective for this direction due to the relative positions of the operator's sphere and the work station. Further research may show the existence of relationships between control of directional forces and work surface positioning with respect to a stationary operator. Consequences of such research would be applicable in determining optimal submersible-manipulator positioning when tasks have been defined in terms of the requirements for the directional application of force.

The overall greater values of the azimuth forces may also be due, in part, to the larger compliance of the shoulder

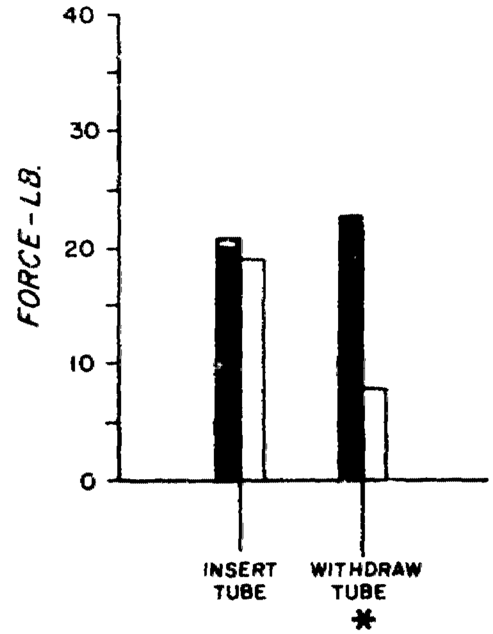


FIGURE 4.2.1 ELEVATION FORCE

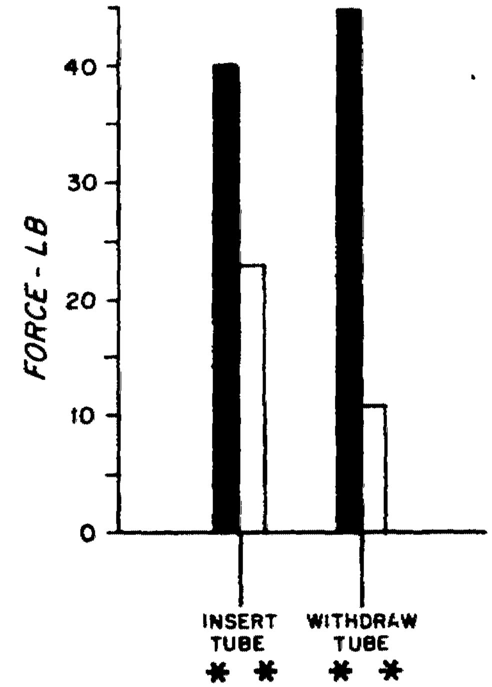


FIGURE 4.2.2 AZIMUTH FORCE

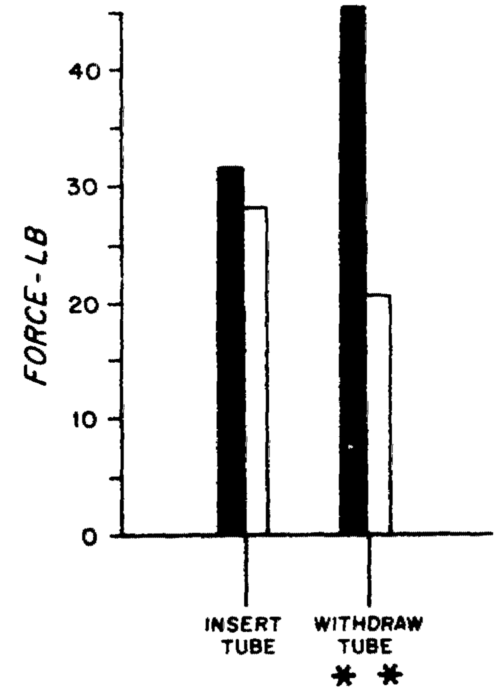


FIGURE 4.2.3 NORMAL FORCE

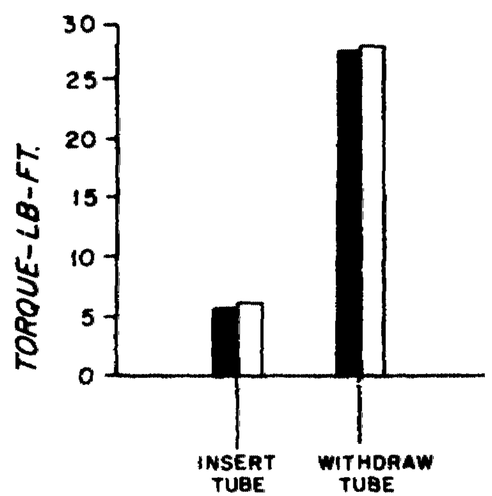


FIGURE 4 2 4 WRIST PIVOT TORQUE

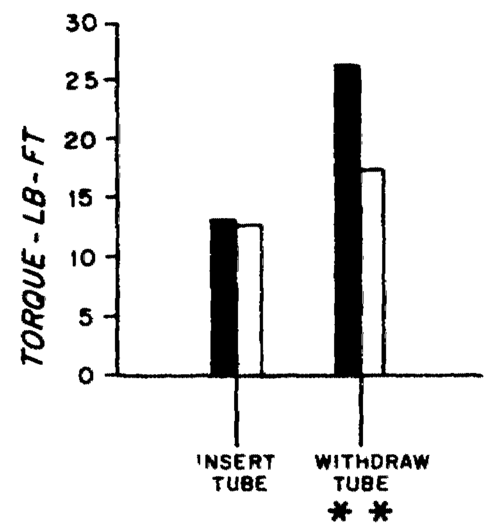


FIGURE 4.2.5 WRIST ROTATE TORQUE

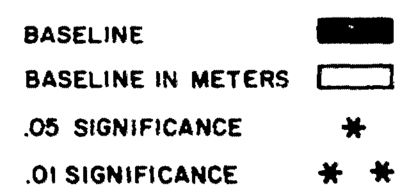


FIGURE 4.2: AVERAGE FORCES AND TORQUES RECORDED DURING CORE TUBE TASK AT 45°

rotate joint which singularly controlled the azimuth force. Small errors in the harness positioning caused relatively large azimuth forces to be applied to the work surface. Similar increases in applied forces are noted in a later section where the results of performance with a low compliance unilateral system are discussed.

The trends occurring in each force vector are shown in the graph of resultant forces in Figure 4.3.1. A considerable increase in force is shown for the withdrawal element of the baseline system, indicating greater operator difficulty in performing this element as opposed to the insertion element. With the addition of meters, this trend seems to reverse itself, as is shown by the graph of force for the meter feedback system. It appears that when operators had the greatest difficulty on the baseline system, they had the least difficulty using the baseline with-meters system. The differences for resultant force between systems were statistically significant at the .01 level.

The results indicated in Figure 4.3.1 seem to indicate that the baseline with meters system provided operators with better control of the component forces of motion. Considering viewport distortion and its effect on visual judgements of depth and alignment, feedback systems may be extremely useful in providing needed supplemental sensory information. Indirectly, operators could use force feedback information to determine the direction of their succeeding motions. Binding forces could be immediately diagnosed and corrective motion initiated. The result would be a reduction of force applied to the tools and apparatus, along with the subsequent economic benefits of a reduction in aborted tasks.

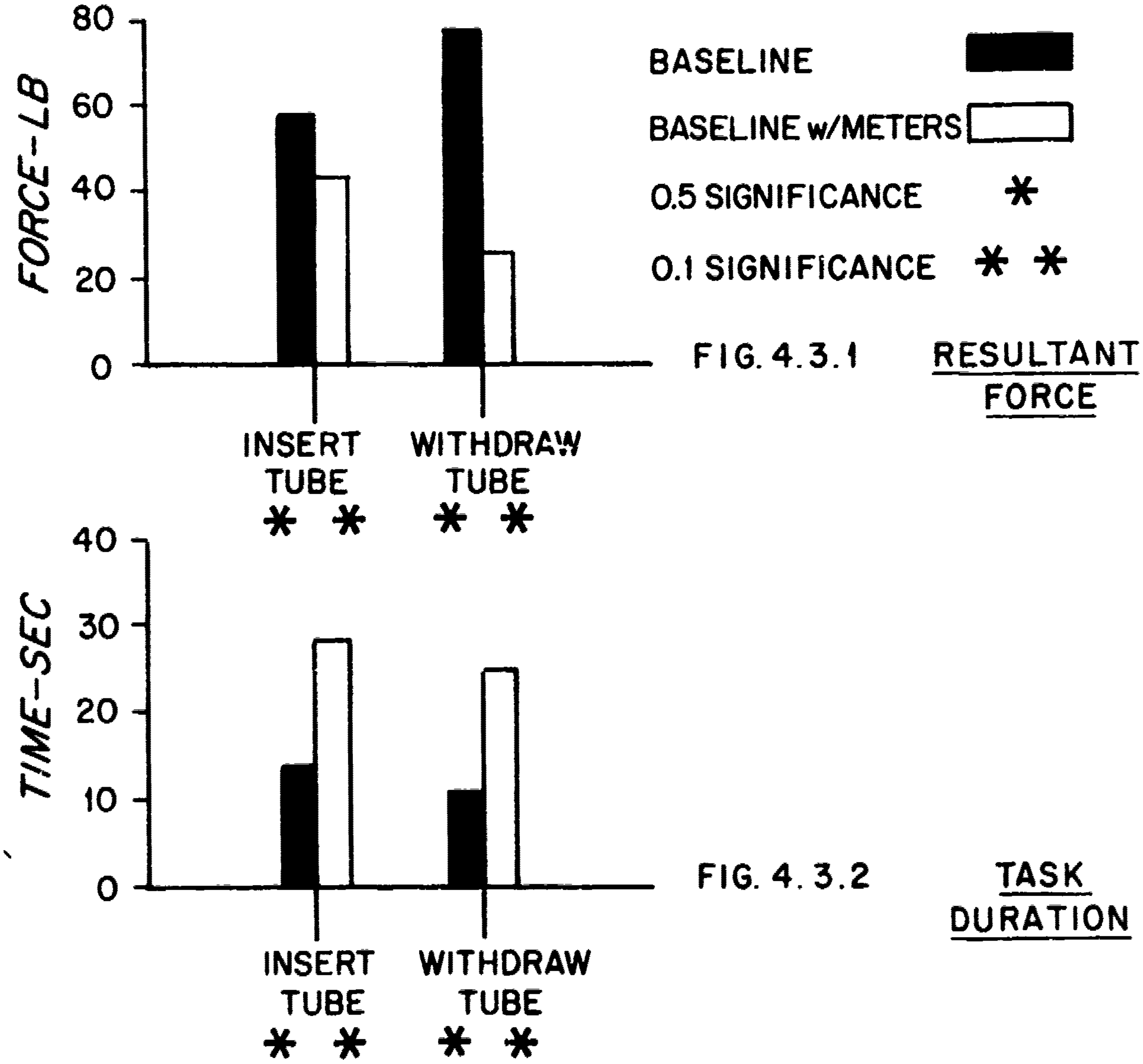


FIG. 4.3

AVERAGE RESULTANT FORCE AND TASK DURATION, RECORDED DURING CORE TUBE TASK AT 45°

These results also suggest that the baseline with meters system would allow the operator to additionally detect and minimize the binding forces introduced by submersible drift. Notice in Figure 4.3.1, that a great amount of force was applied while withdrawing the tube without the use of meters. The operator had no clue of the binding force present in the system. The meter display allowed detection and minimization of these forces during this same operation.

Figures 4.2.4 and 4.2.5 show average wrist forces applied across both task elements. Differences in wrist pivot forces between system were found to be nonsignificant. However, differences between task elements appear to be considerable for both systems. Forces are greatly increased during core tube withdrawal for both systems, indicating difficulty in operator wrist alignment during this element, independent of system type. This conclusion is supported by similar differences in wrist rotate forces in both task elements. Values of wrist rotate force recorded for the withdrawal elements of each system are statistically separable at the .01 level. Although the operators received no force feedback information for wrist forces, they were able to significantly reduce wrist rotate forces with the usage of visual feedback meters. This may be due to an interdependence between azimuth and wrist rotate forces. By controlling azimuth forces, operators were effectively able to reduce wrist rotate forces acting in the same direction. Wrist forces do not provide as clear an indicator to performance changes as do the major directional forces. However, the importance of controlling wrist forces may become greater as a function of task type.

4.2.2 Time Recorded During Core Tube Task at 45°

Large differences between systems in operator performance times were found to be significant at the .01 level. Figure

4.3.2 shows that on the average, operators with meters required approximately twice the amount of time in both task elements to perform the task. These differences may be attributed to an increase in operator workload precipitated by the addition of feedback meters. It may be true that the additional information provided by the meters necessitates an extension of the time requirements for operator processing. If a relationship does exist between performance time and the amount of information provided, further research employing a greater number of feedback meters for the same task, should show even longer performance times. This, however, may be a hasty assumption, since usage may also be a function of the other variables, such as task complexity. In this task, it appears that operators were taking advantage of the available feedback information, as is indicated by the large differences in performance times.

4.3 PERFORMANCE EVALUATION OF CORE TUBE TASK AT VERTICAL

This task was a replicate of the core tube task previously described with one exception. The angle at which the sheathe was supported was changed to vertical. The angle change was made to increase task difficulty.

4.3.1 Force Control Behavior Recorded During Core Tube Task At Vertical

The data showed results similar to those of the previous core tube task. Forces measured in the three vectors of motion generally showed lower values for the meter feedback system. Figure 4.4.1 shows average elevation forces for both systems. Significant system differences occur at the .05 level for both insertion and withdrawal elements. Comparing these data to those of the previous task, Figure 4.2.1, one major difference becomes apparent. Although operator performance on the

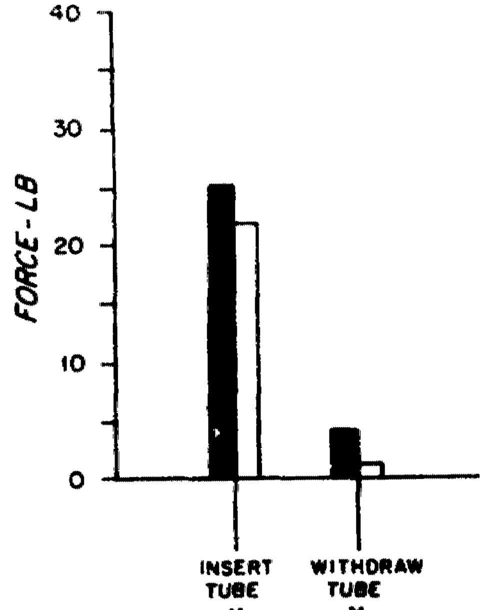


FIGURE 4.4.1 ELEVATION FORCE

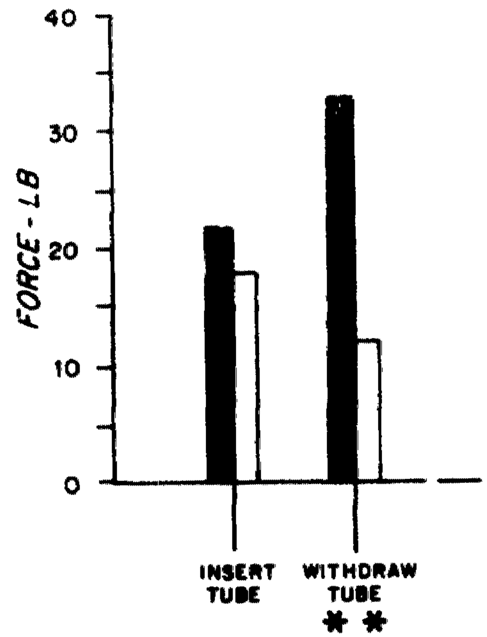


FIGURE 4.4.2 AZIMUTH FORCE

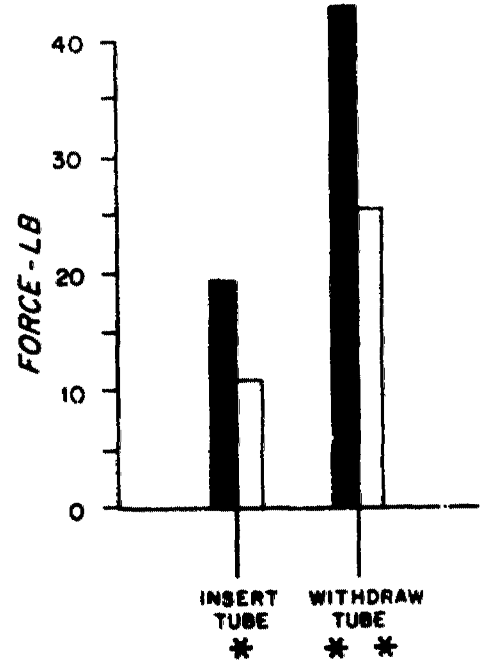


FIGURE 4.4.3 NORMAL FORCE

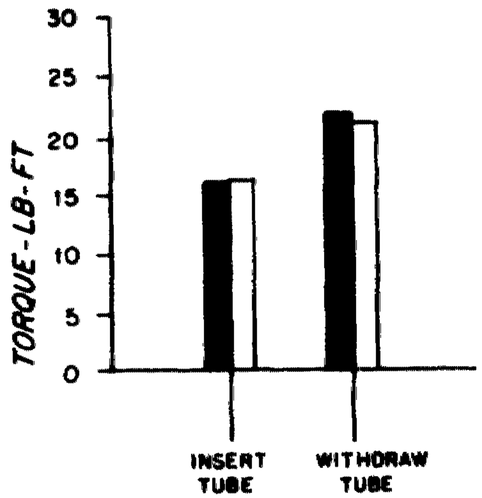


FIGURE 4.4.4 WRIST PIVOT TORQUE

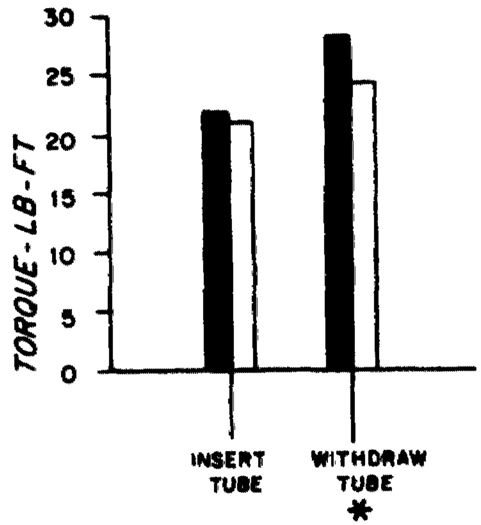


FIGURE 4.4.5 WRIST ROTATE TORQUE

BASELINE
BASELINE w/METERS
.05 SIGNIFICANCE *
.01 SIGNIFICANCE * *

FIGURE 4.4 AVERAGE FORCES AND TORQUES RECORDED DURING CORE TUBE TASK AT VERTICAL

feedback system showed similar trends for both core tube tasks, a large reduction in the magnitude of elevation forces during withdrawal using the baseline system is evident in the vertical sheathe task. Knowing that elevation forces correspond to forces exerted by shoulder pivot joint, this reduction may be explained by considering changes in motion required. In the core tube task at 45°, the motion required for task completion involved coordination of the shoulder pivot and elbow flexion joints. The forces recorded were, in effect, caused by the deviation of motion of these two major joints.

By shifting the angle of the sheathe to vertical, motion has been effectively reduced primarily to the elbow-flexion joint. Once the shoulder pivot has been accurately positioned, the majority of the motion may be completed by elbow flexion (a slight shoulder pivot joint motion is required). Figure 4.4.2 shows smaller azimuth forces were applied during both task elements than those previously reported for the 45° task in Figure 4.4.2. Figure 4.4.3 shows smaller normal force values for the visual feedback system statistically significant at the .01 and .05 levels for insertion and withdrawal, respectively.

On the average, resultant forces were generally lower when the sheathe was supported at 90° than when at 45°. Significant differences between systems were found at the .01 level for both the insertion and withdrawal elements, with reduction occurring on the feedback system, as shown in Figure 4.5.1. The relationship between operator and work stand positioning may better explain the nature of these differences occurring with sheathe angle.

The wrist moments recorded during the core tube task at a vertical angle bear a striking resemblance to the data recorded for the previous task. Data in Figure 4.4.4

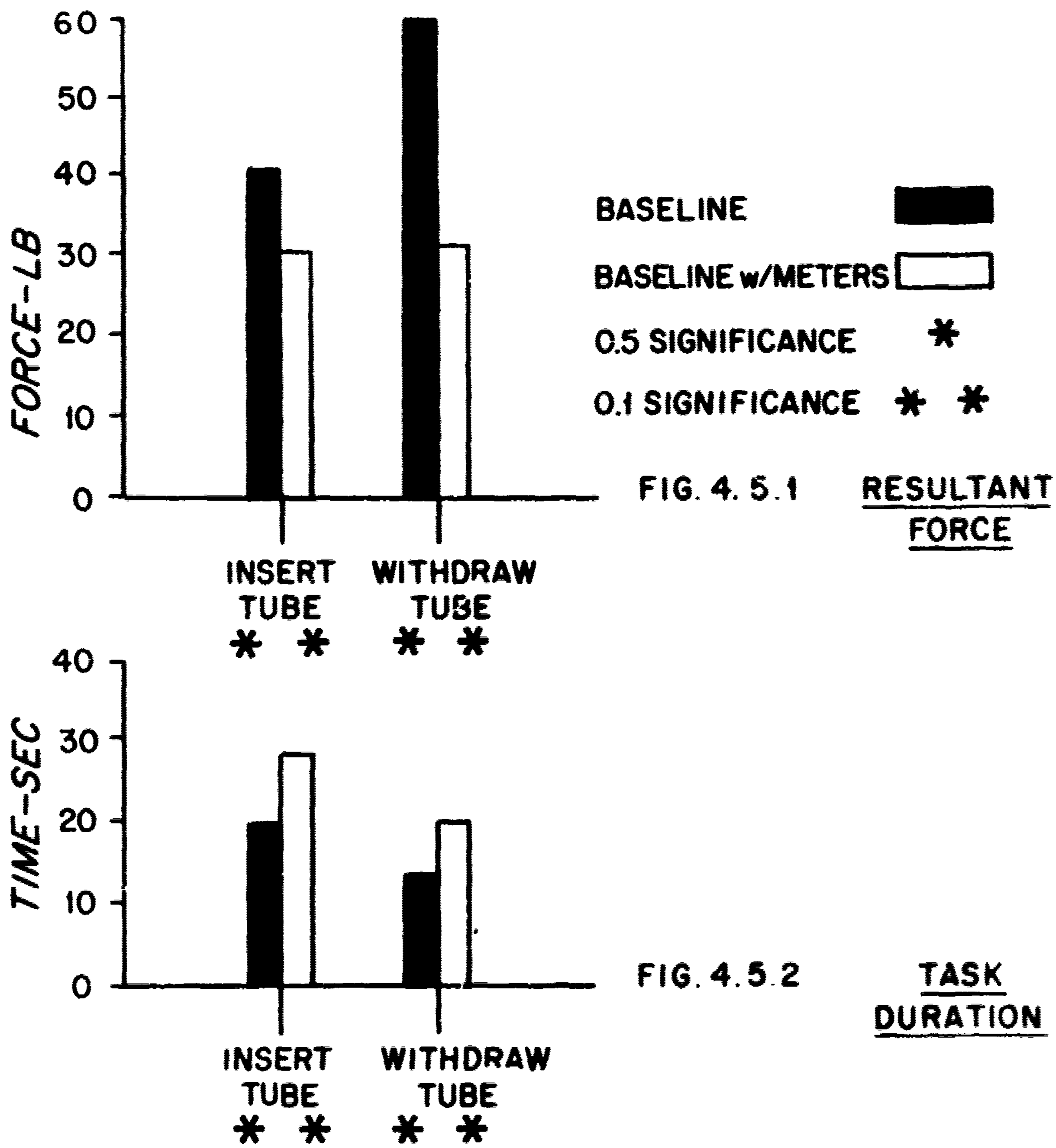


FIGURE 4.5 AVERAGE RESULTANT FORCE AND TASK DURATION RECORDED DURING CORE TUBE TASK AT VERTICAL

similar to that in 4.2.4, indicate no difference between wrist pivot forces relative to the two systems. Withdrawing the core tube, however, required overall larger magnitude moments. Visual force feedback can be seen in Figure 4.4.5 to reduce wrist rotate forces during the withdraw task element, statistically significant at the .05 level. As it is the function of the wrist rotate joint to transmit the azimuth forces along the arm to the tool, it is not surprising to find a reduction in wrist rotate forces corresponding to the reduction of azimuth forces. This, however, does not explain why no reduction is evident in the insert tube task element. Perhaps a better measure of performance would have been the moments applied to the work surface about the azimuth, elevation and normal axes. It is difficult at this level of analysis to interpret the results indicated by the individual wrist joint moments.

4.3.2 Time Recorded During Core Tube Task At Vertical

Statistically significant differences in operator performance times were found at the .01 level for both elements of this task. Figure 4.5.2 indicates measurements which are similar to those of the 45° core tube task, Figure 4.3.2. More time is required with the visual feedback system. Implications of meter usage are consistent with those stated previously, assuming that the complexity of this task closely approximated that of the previous core tube task. Operators used slightly less time to withdraw the core tube than to insert it for both systems.

4.4 PERFORMANCE EVALUATION OF SAMPLE RETRIEVAL TASK

This task consisted of grasping an aluminum block, transporting the block, and depositing it into a container. The operator's objective was to minimize grip force throughout the task. Grip

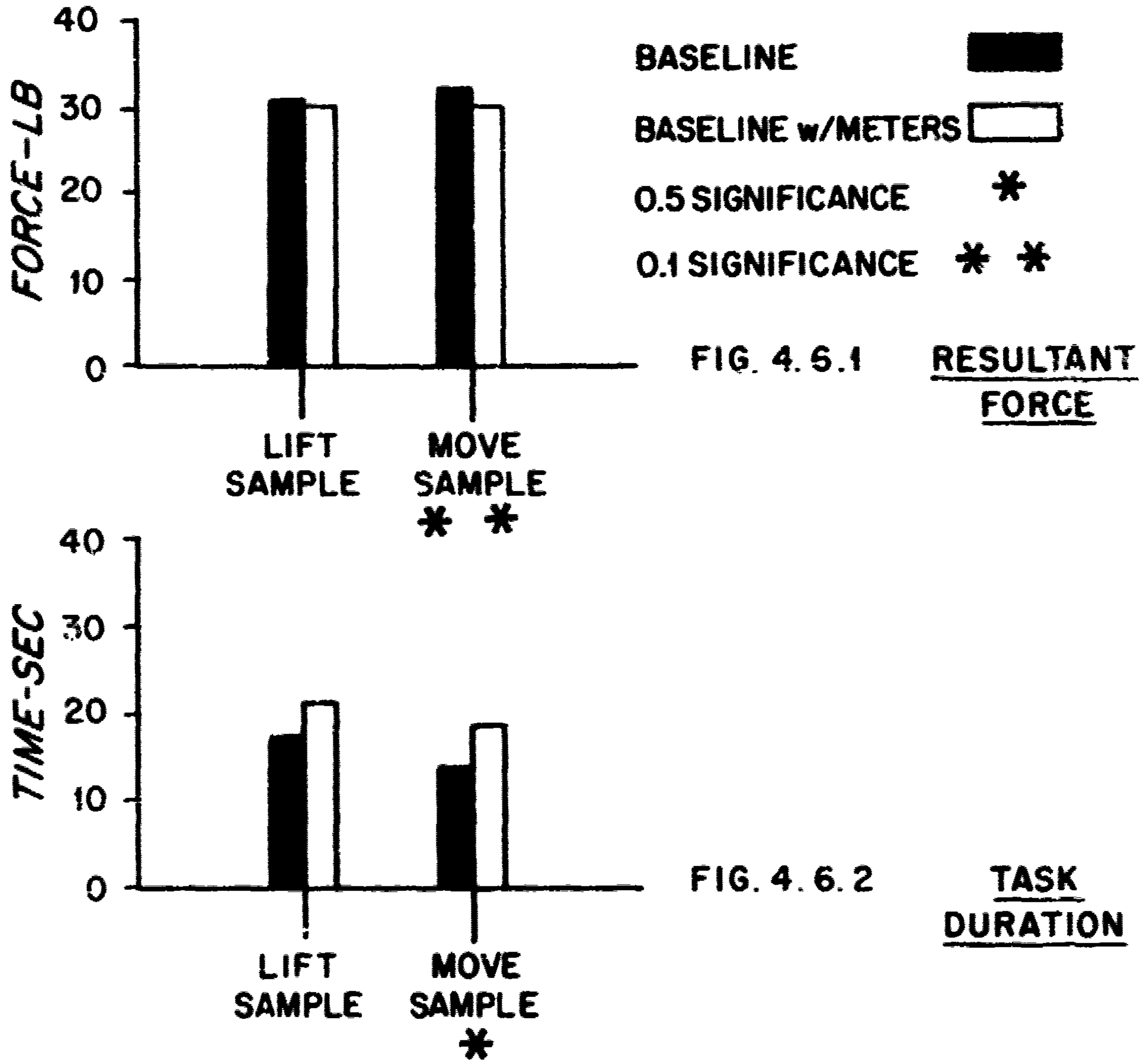


FIGURE 4.6 AVERAGE RESULTANT FORCE AND TASK DURATION RECORDED DURING SAMPLE RETRIEVAL TASK

forces were recorded over two time segments; lifting and moving. All other forces indicated only acceleration motion and were not recorded.

4.4.1 Force Control Behavior Recorded During Sample Retrieval Task

Figure 4.6.1 illustrates grip force measurements over each task element. A slightly lower grip force was recorded for the lifting element across all subjects using the baseline with meters system; however, this difference was not statistically supportable. A greater difference between systems showing a reduction of force for the baseline with meters system, occurred during movement of the block. This was found to be significant at the .01 level. On the average, operators had a tendency to exert a greater grip force during motion. Significantly, they were able to control grip force and effectively overcome this tendency, given the ability to monitor force. This is evident by the constant force exertion exhibited across task elements when operators employed the meter feedback system.

4.4.2 Time Recorded During Sample Retrieval Task

In general, task performance times were greater for the baseline with meters system. Figure 4.6.2 shows greater times for this system over both task elements, however, the only statistically supportable difference occurs during the motion element. The larger task performance times found with the meter feedback system are consistent with the findings for the tasks previously described. The results of this task, again, seems to indicate the existence of a relationship between performance time and information display was previously hypothesized.

4.5 PERFORMANCE EVALUATION OF SURFACE FOLLOWING

This task simulated the use of an underwater torch to cut a closed circular path eight inches in diameter. A router was used to simulate the cutting torch. The surface which was cut had been skewed to an angle of 45° to position it normal to the F_N axis of the manipulator arm. This was undoubtedly the most difficult task performed in the experiment. The operator's objective involved minimizing normal forces while maintaining tool alignment with the surface and circle outline. Forces were recorded over each two basic motions occurring in the task. The motions included a downward pulling sweep of 180° and a similar upward pushing sweep to complete the circle.

4.5.1 Force Control Behavior Recorded During Surface Following

The only significant differences between systems in this task occurred during the element of downward motion. Figure 4.7.1 shows the average forces in elevation recorded for both systems, with no supportable differences found. Notice the force differences between task elements of downward and upward motion. The graph shows forces in the upward motion element to be almost double the force recorded during the downward element for both systems. Similar results were found on the visual feedback systems for azimuth forces and on both systems for normal forces. It appears that there was less difficulty involved on the part of the operator in the performance of the downward motion than that of the upward motion. For the downward cut, motion consisted of pulling the tool with coordinated elbow flexion, shoulder pivot and shoulder rotate motion. A similar pushing motion defined the upward cut. Operators consistently performed the downward motion with more control and less force exertion

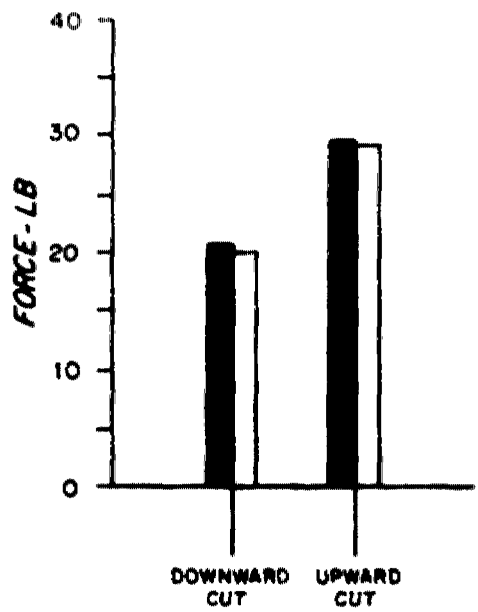


FIGURE 4 7 1 ELEVATION FORCE

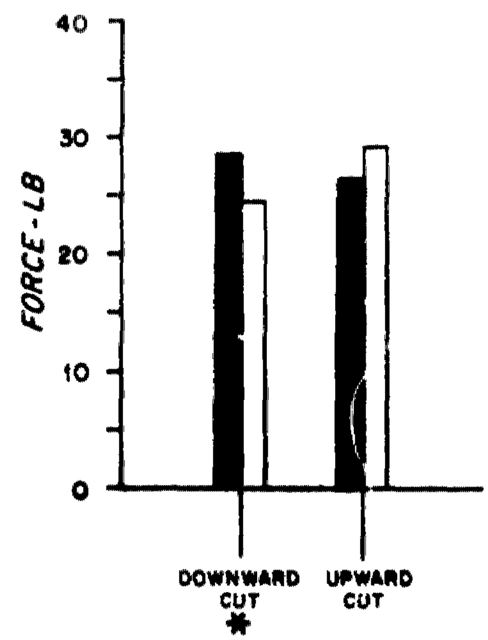


FIGURE 4.7.2 AZIMUTH FORCE

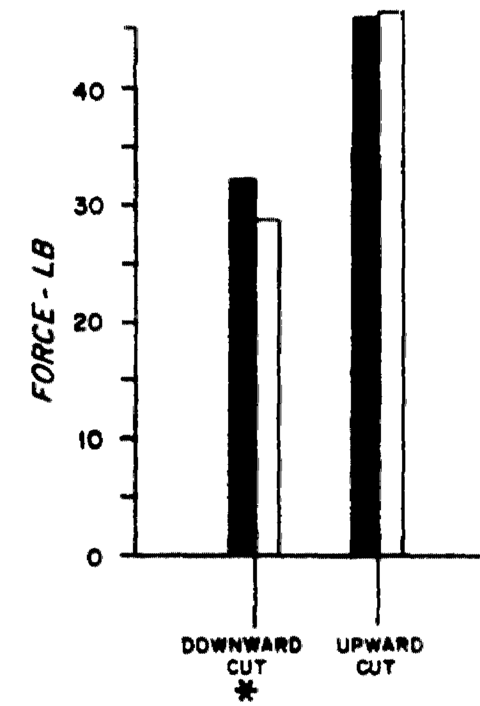


FIGURE 4 7 3 NORMAL FORCE

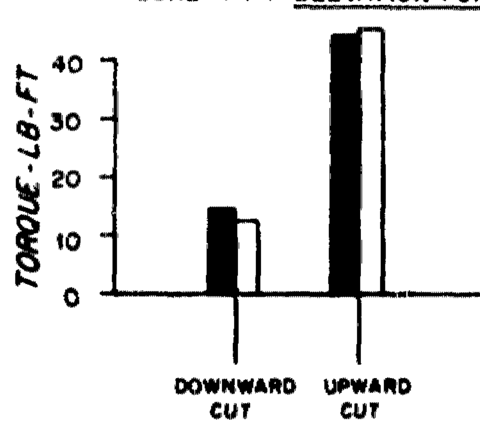


FIGURE 4 7 4 WRIST PIVOT TORQUE

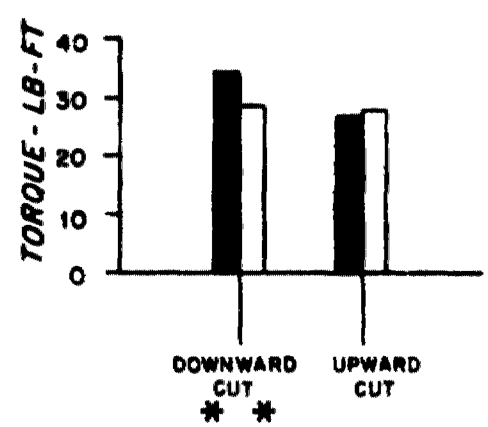


FIGURE 4 7 5 WRIST ROTATE TORQUE

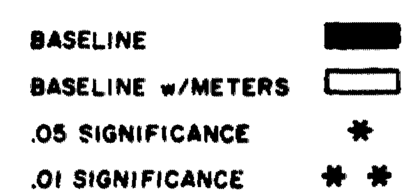


FIGURE 4 7 AVERAGE FORCES AND TORQUES RECORDED DURING SURFACE FOLLOWING TASK

than they did with the upward cut. This finding is also supported by accuracy measurements obtained from scoring the cut surfaces. Scoring was based on measurements of deviation from the circular outline, length of continuous cut and depth of cut as a measure of perpendicularity. It was found that operators performed the downward motion more accurately than the upward motion in 44% of all trials, while the converse occurred in only 13% of all trials. No identifiable differences were observed in the remaining 43% of the samples. These findings are based on subjective evaluation of (1) length of uninterrupted cut, (2) depth of cuts, and (3) deviation from path. This trend is also supported by the results found for wrist pivot forces. Figure 4.7.4 indicates much greater force exertions during the upward element of performance on both systems. Wrist rotate indicates equivalent force application, Figure 4.7.5, since this joint is primarily concerned with right/left motion. The reasons for these differences in performance between task elements are not obvious. Further investigation may reveal that such variables as operator coordination, control harness design, manipulator arm characteristics, or some combination of these have an influencing effect on performance during each task element. Figure 4.7.2 and 4.7.3 show azimuth and normal forces which are statistically separable in the downward element, significant at the .05 level. Visual feedback allowed somewhat better force control. A summary of these trends appears in the graph of resultant forces in Figure 4.8.1. The graph illustrates that the only instance in which the addition of feedback meters significantly reduced force occurred in the downward element of motion, which was supportable at the .05 level. It also shows much larger forces for both systems during the upward motion element.

FIGURE 4.7 AVERAGE FORCES AND TORQUES RECORDED DURING SURFACE FOLLOWING TASK

4.5.2 Time Recorded During Surface Following

The average performance times recorded for this task vary inversely with forces exerted for both task elements. Generally, operators exerted less force when they spent more time in performing this task, as is evident by a relatively low force measurement for the downward element of motion. Figure 4.8.2 shows a high duration for this same task element. It is also shown that when the operators' task duration times were lower, their corresponding amounts of applied force were higher. An interesting phenomenon occurs in this task which has not occurred in any other task. Performance times recorded for the baseline system were slightly higher than the meter feedback system, although not significantly so. In all other tasks, performance times for the baseline-with meters system had been significantly higher than the baseline system.

The major difference between this task and all others lies in the greater degree of difficutly required to accurately perform the task. Complete visual attention was necessary to maintain perpendicular alignment with the surface and circle outline. Because of this difficulty factor, operators had a tendency to ignore the meter feedback information that was available. The fact that performance times for both systems were nearly equal for each task element may indicate that the operator behavior did not change as a function of system type. On the other hand, this lack of performance difference may be attributable to the tool design. Excessive application of force on this tool caused a mechanical compression of shock absorbers. This was easily seen by the operator and may have provided the primary source of force feedback information. Similar performance between systems would, therefore, be expected. If we assume the hypothesis presented earlier to be

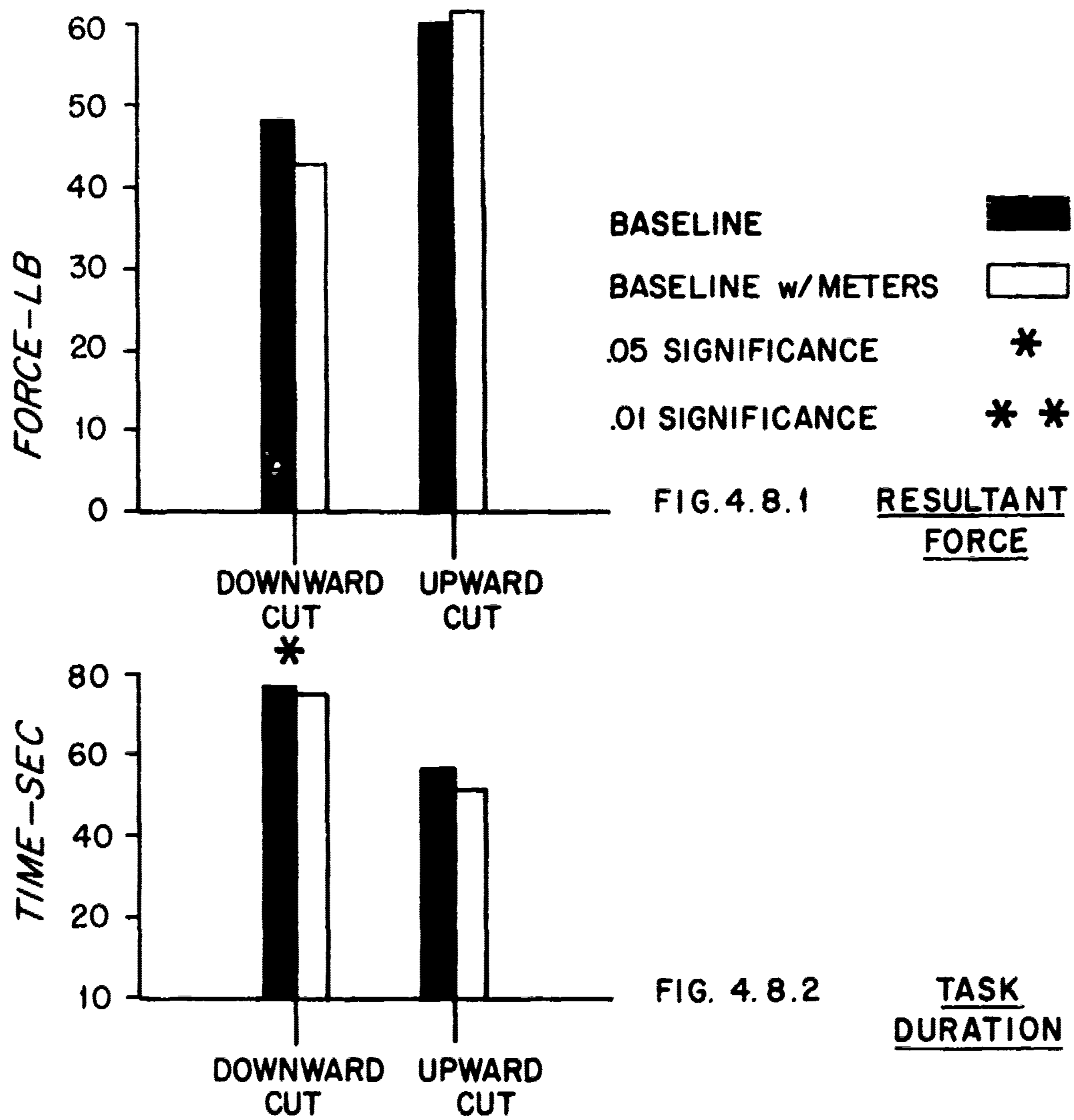


FIG. 4.8.1 RESULTANT FORCE

FIG. 4.8.2 TASK DURATION

FIGURE 4.8 AVERAGE RESULTANT FORCE AND TASK DURATION RECORDED DURING SURFACE FOLLOWING TASK

true, (i.e., additional information received requires additional operator processing time as supported by the results of previous tasks), then we must conclude that the operators did not use the feedback meters in this task, or at least their usage was limited to the downward element of motion. In the more difficult upward motion, the force feedback information provided seemed to have no effect on operator performance.

4.6 PERFORMANCE EVALUATION OF DRILLING TASK

This task required the operator to drill a ½" hole in an aluminum plate. The plate was supported at an angle of 45° from the vertical normal to the F_N axis of the manipulator arm. The drill was bolted to the manipulator arm and required no operator control to hold it. It was the objective of the operators to minimize force in all directions while drilling a hole on a line perpendicular to the surface of the plate, clearing the hole, and withdrawing the drill bit from the hole along that same line.

4.6.1 Force Control Behavior Recorded During Drilling Task

Figure 4.9.1 indicates that extremely small amounts of elevation force were exerted in this task by both systems. No statistical differences between systems were found for elevation forces, however, the baseline with meters systems allowed operators to perform slightly better. These results show essentially no force was applied by the shoulder pivot joint in either task and seem to imply that operators had a tendency to keep this joint rigid throughout the task. High force values, shown in Figure 4.9.3 of normal forces, indicate that operators supplied drilling force almost entirely through the elbow flexion joint. Large normal forces were recorded

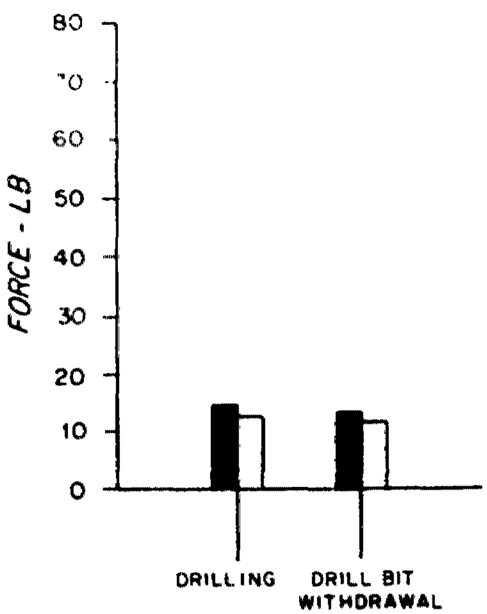


FIGURE 4 9 1 ELEVATION FORCE

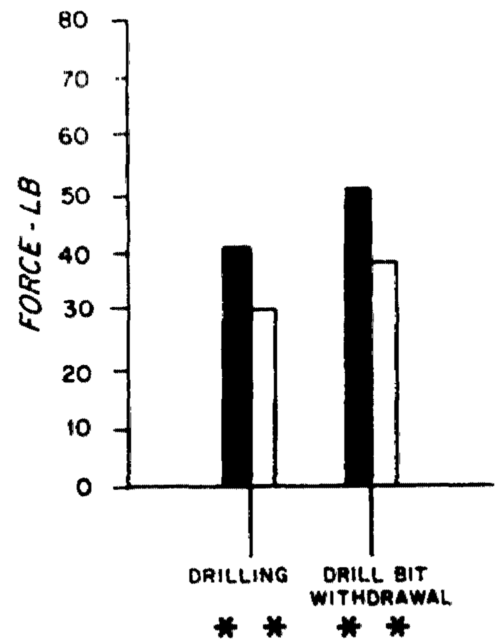


FIGURE 4 9.2 AZIMUTH FORCE

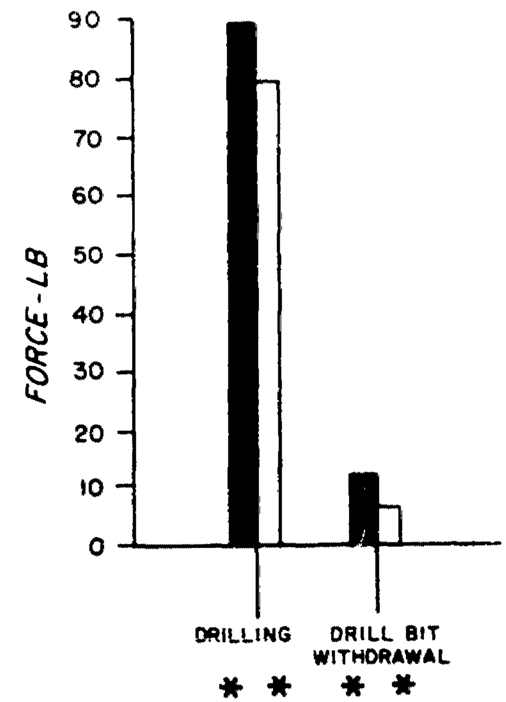
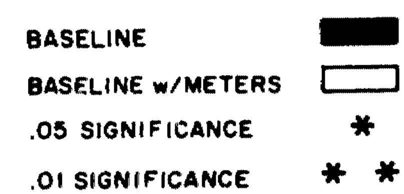


FIGURE 4.9.3 NORMAL FORCE



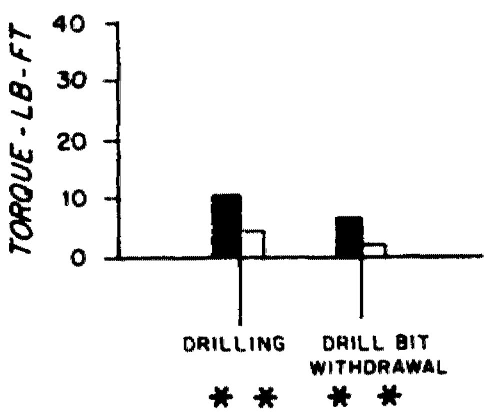


FIGURE 4 9 4 WRIST PIVOT TORQUE

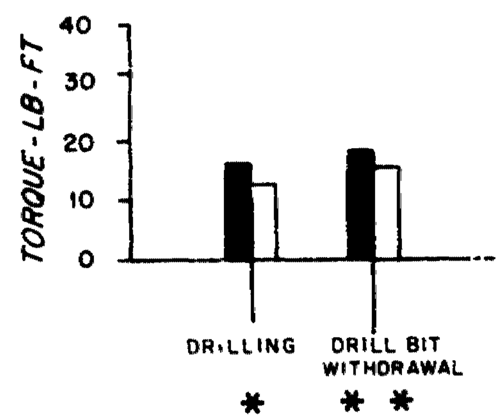


FIGURE 4.9.5 WRIST ROTATE TORQUE

FIGURE 4.9 AVERAGE FORCES AND TORQUES RECORDED DURING DRILLING TASK

for both systems during the drilling element of the task. It was found, however, that the operators used somewhat less normal force with the use of feedback meters. This is shown by a significant reduction in normal force for the baseline with meters system, supportable at the .01 level. A similar force reduction which occurred during the withdrawal element of this task was also found to be significant at the .01 level.

Although operators were able to perform the withdrawal element with a high degree of force control, it appears that they had some difficulty in coordinating the straightline withdrawal motion needed to perform the task with minimal force. Deviations in the azimuth direction from the ideal force-minimizing path seem to be the greatest during the withdrawal element of operator performance. Figure 4.9.3 shows average azimuth forces for both control systems and task elements. Overall, operators exerted a greater azimuth force in the withdrawal element, regardless of which control system they employed. The fact that azimuth forces were present at all is indicative that errors in operator judgement of depth perception or a lower system compliance in this direction contributed considerably to the total output of force. Ideally, no azimuth forces are required to complete this task. However, the respective positioning of the operator and work stations may have caused the operator to believe motion in the azimuth direction was necessary. It appeared more difficult to judge alignment in this direction. Errors in depth judgment and motion appear to have been reduced by providing force feedback meters which indicate forces in the depth direction. Based on similar core tube task results, it was not surprising to find that operators were better able to control forces in this direction while operating the baseline with meters system. Differences between azimuth forces were found to be statistically supportable at the .01 level for both the drilling and withdrawal elements.

A general view of operator force exertion is provided by a plot of resultant forces in Figure 4.10.1. It is again shown that operator performance improved with the addition of force meters. Differences between systems were statistically significant at the .01 level for both task elements. A very important finding of the drilling task was the reduction of wrist torques with the use of visual force feedback. Figures 4.9.4 and 4.9.5 indicate that both wrist pivot and wrist rotate torque are reduced by visual feedback. These torques are generally responsible for imposing the bending moments which cause breakage of drill bits. These findings imply that, perhaps, it is sufficient to display just the force vector applied to the work surface and not force vectors and moments. The moments appear to be limited through the use of just force vector displays.

4.6.2 Time Recorded During Drilling Task

In general, performance times for this task were increased with the addition of feedback meters. Times for the baseline with meters system were greater in both the drilling and withdrawal task elements. Statistically supportable differences were found only in the withdrawal element, however. These results were consistent with those found for all other tasks performed, except the surface following task. Figure 4.10.2 indicates that operators generally spent a much greater amount of time in drilling the hole as compared to the time spent in withdrawing the drill bit from the hole. This trend occurred for operators using either system.

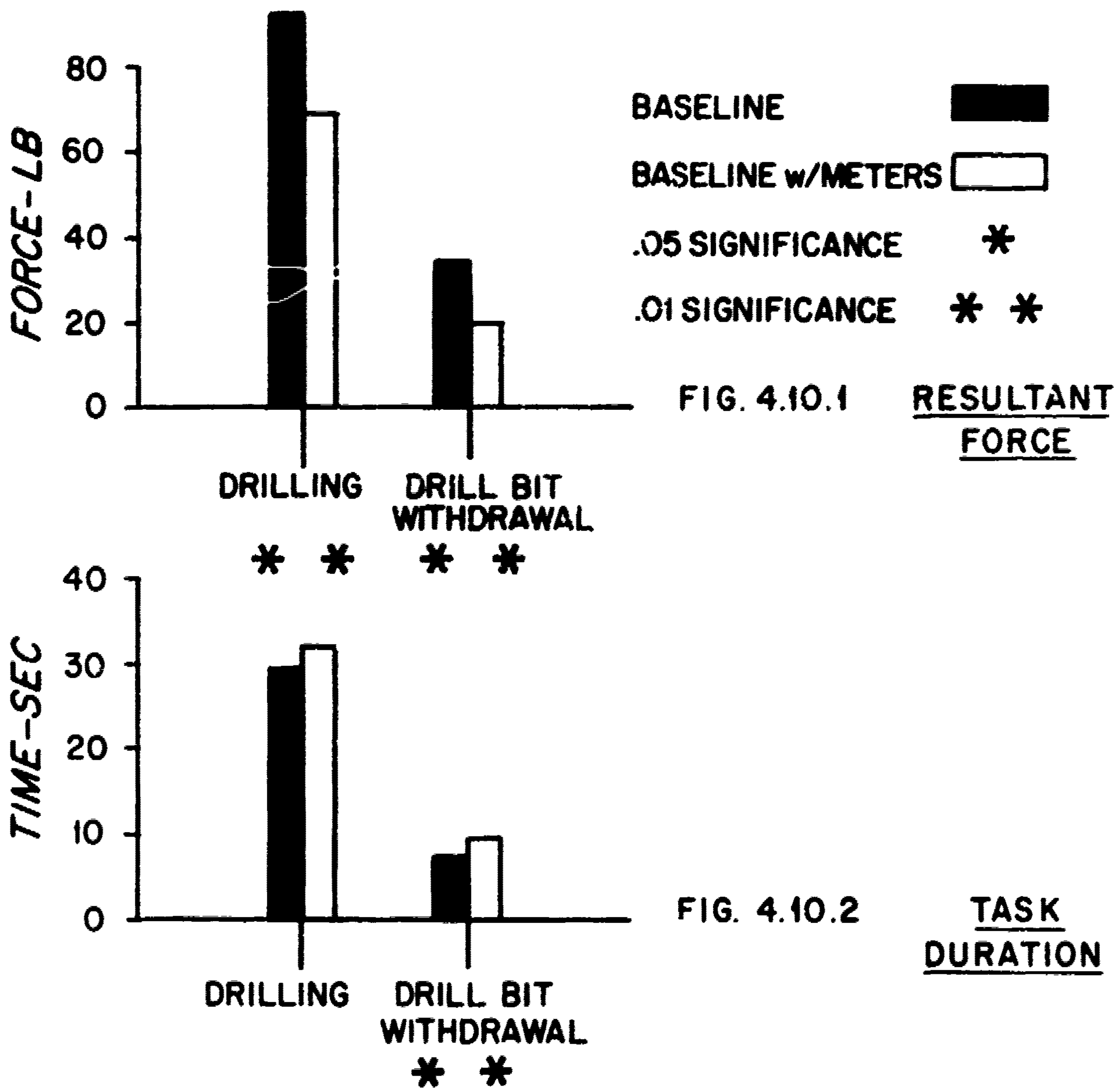


FIG. 4.10
AVERAGE RESULTANT FORCE AND TASK DURATION, RECORDED DURING DRILLING TASK

SECTION 5

EVALUATION OF CONTROL PERFORMANCE

The results of this research seem to indicate that visual force feedback will significantly affect operator performance for tasks within some specific range of difficulty. These effects, however, must be evaluated in terms of explicit applications, and variable restrictions within those applications. The following is a discussion of these applications and variable restrictions.

5.1 CONTROL OF APPLIED FORCE

If for a particular task, minimization of forces exerted to tools and/or delicate instruments is the most constraining requirement, it appears that a force feedback system, similar to the baseline-with meters system tested in this experiment, would be more successful in reaching this objective than would a system without meter feedback information. Figure 5.1.1 illustrates that operators were able to significantly reduce resultant forces exerted in at least one (more often both) of all task elements defined. At no time did operator performance for the baseline-with meters system significantly increase force exertions in any task element. The magnitude of these force reductions appears to be indirectly related to task difficulty. Smaller differences between systems were found in the surface following task, than were found in any other task. These small differences may be attributable to the fact that this task was confounded with other visual feedback and demanding in terms of operator concentration.

It appears that in tasks as difficult as the surface following task, performance requirements may impart limitations on the operators ability to monitor visual feedback information. The

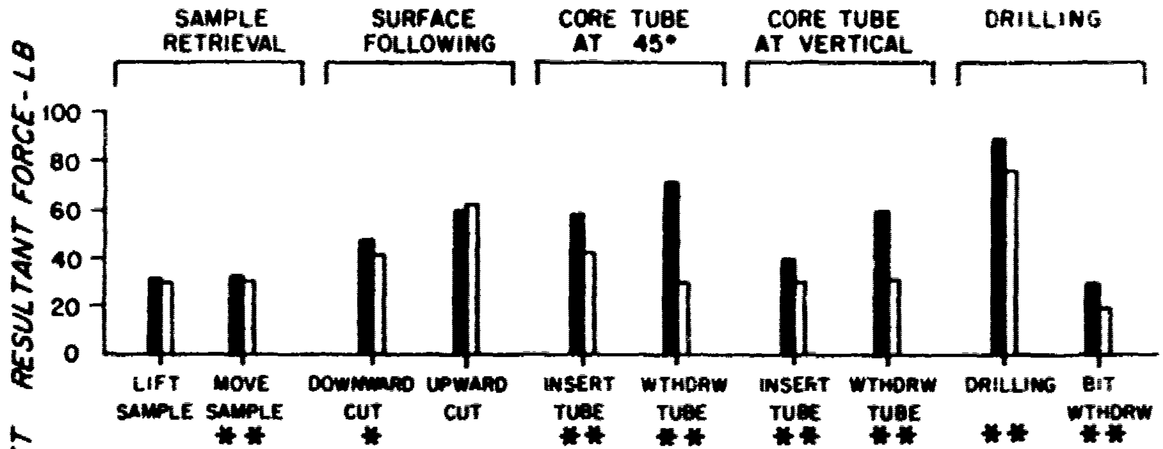


FIG 5.1 1 AVERAGE RESULTANT FORCE APPLIED DURING TASK BEHAVIOR ELEMENTS

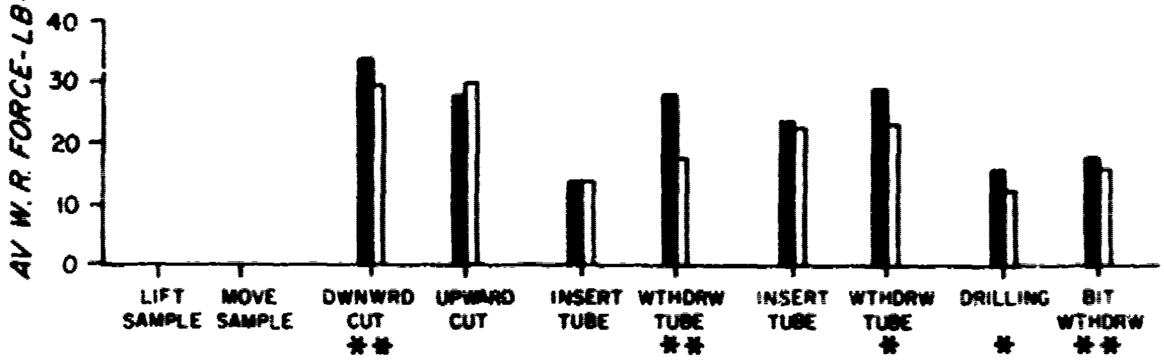


FIG 5 1 2 AVERAGE WRIST ROTATE FORCES APPLIED DURING TASK ELEMENTS

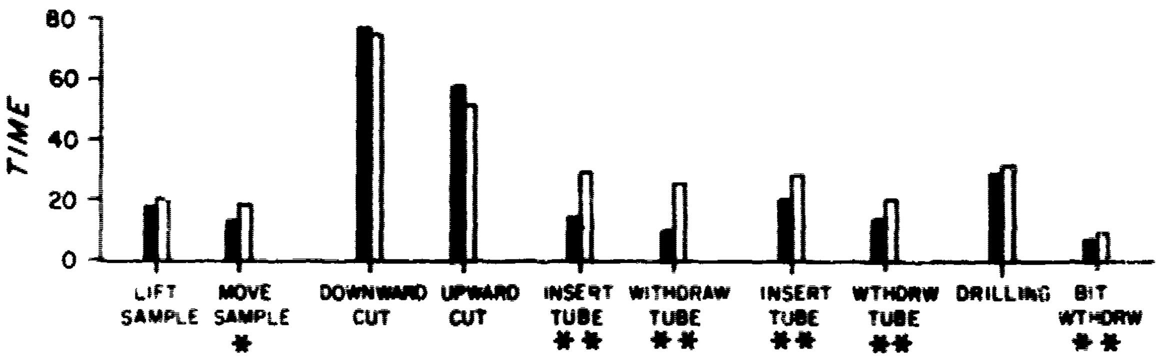


FIG 5 1 3 AVERAGE TIME DURATION OF TASK ELEMENTS

KEY BASELINE ▬ BASELINE w/METERS ▭ .05 SIGNIFICANCE * .01 SIGNIFICANCE **

FIG 5.1 SUMMARY OF PERFORMANCE DATA ACCORDING TO TASK BEHAVIOR ELEMENTS

operator's attention must fully be concentrated on the performance of the task. The existence of some specific difficulty range for task performance is implied by these findings. Further investigation may reveal the upper and lower limits of the range of tasks wherein force feedback systems may be effectively employed, however, the development of a set of meaningful difficulty measurement criterion is a prerequisite for such an evaluation.

Directing our attention to optimum display design, the question of how much information to be displayed arises. The baseline-with meters system displayed only grip force and an orthogonal set of three applied force vectors. A full description of the forces applied to the work surface must also include applied moments. A review of all the task completion times indicates that utilization of just the force vector information usually increased task performance times. The additional display of the three moments, acting on the work surface about the force vector axis would in all probability, further increase task performance times. Wrist rotate torque data, Figure 5.1.2 indicate that such an additional display may be unnecessary. The wrist torques (an indirect measure of moments applied to the work surface) were generally reduced when the baseline-with meters system was utilized. Little additional moment control may be attained through the provision of a more complex display. Additional display complexity may in fact reduce performance with regard to force control and task duration.

Another factor involved in the minimization of forces may consist of the operator/work-station positional relationships. Task performance may be adversely affected by inaccurate operator estimations of distance in the direction which defines depth. Such inaccuracies could lead to an excess exertion of force in this direction, which in our case represented the azimuth direction. Note that similar errors in judgement

presumably occurred in the elevational and normal directions, but since the operator had a more well defined view of the directions, the inaccuracies were comparably small. On the baseline-with meters system, the information provided served as a guide to the operator. Errors of judgement in spacial measurements could be corrected by observing the corresponding directional force meters. The operators were able to significantly reduce forces throughout most of the tasks, given the opportunity to acknowledge this information. When certain restrictions are placed on force exertions in a particular direction, it may be of value to have some method for determining the operator position which, with respect to a particular work surface, will allow optimum force control in that direction. Additional analysis may show which characteristics, not only of the operator/work-station positioning, but also of the control harness positioning as well, have an influencing effect on operator performance.

System compliance also seemed to affect the magnitude of forces applied to the work surface. Joints with lower compliance were consistently seen to contribute to more applied force. It is possible to conjecture that performance of similar tasks with an extremely stiff rate controlled arm (compliance near zero) would increase applied forces another order of magnitude. It is of note that the applied forces recorded during the tasks fell well below the maximum of payload force capacity of the manipulator arm as noted on Table 3.1. Stiffer rate controlled arms might be expected to operate closer to the maximum force limit.

5.2 DURATION OF TASK PERFORMANCE

Data in Figure 5.1.3 indicate that performance times were con-consistently higher when operators used the baseline-with meters system. Significant differences between systems were usually found in all behavior elements of every task except

the contour cutting task. This indicates the need for additional time for operator processing of the information provided by feedback meters. Clearly, an increase in the operator workload seems necessary if the force meters are to be observed. The operator is performing the same task but receiving a considerably greater amount of visual information than would normally received without meters. The operators rate of performance is retarded by this additional burden. The fact that performance times increased in all but the surface following task seems to prove that operators will generally use feedback information from meters for tasks at certain difficulty levels. The fact that no significant differences in performance times were found in the surface following task lends support to the notion that this task was outside of the difficulty range in which force feedback meters enhance operator performance. It appears that the high difficulty factor severely hampered the operators ability to monitor feedback information.

SECTION 6

SUMMARY

6.1 MAJOR FINDINGS AND ACCOMPLISHMENTS

The following findings and accomplishments summarize the results of this research program: they are presented in categories representative of the various areas of the program.

6.1.1 Experimental Evaluation of an Undersea Manipulator with a Visual Force Feedback Display

- Utilization of a unilateral position controlled manipulator system, with high compliance and a rapid time response, facilitated the execution of both close tolerance and surface following tasks which are acknowledged to be very difficult to accomplish with current unilateral position and rate controlled manipulators.

- Provision of a visual force feedback display resulted in an average reduction of applied force of 34%

- Provision of a visual force feedback resulted in overall:
  - Less grinding force on tools and bits
  - Few task aborts
  - Less potential damage to the slave manipulator and work surface

Utilization of a visual force feedback display required the operator to time share his visual patterns between the displays and the work surface. This usually resulted in an increased task completion time. The average increase in task time recorded during our experimental tasks was 42%.

·Provision of a visual force feedback display should aid the operator in sensing and responding to forces applied to the work surface as the result in submersible drift.

6.1.2 Manual Control Behavior Patterns Relative to Force Feedback Manipulators

·Successful performance of certain tasks is dependent on the operator's ability to control the application of force and torque by the manipulator. This research showed that the vector forces applied to the work surface are controlled principally by the upper arm joints and that torques applied to the work surface are controlled principally by the wrist joints.

·There are experimental indications that utilization of visual force feedback displays allowed the operator to better control force vectors applied along the operator's line of sight.

·Difficult tasks occasionally saturate the visual sensory channel precluding the effective use of the force feedback information provided on the meters.

·Provision of visual force feedback information aids in the control of motion when the manipulator's motion is mechanically confined.

·The operator's ability to control force on compliant unilateral position controlled systems with and without visual force feedback varies directly with the degree of compliance in the system itself. (i.e., higher compliance, better force control.)

- A limited amount of operator control of the rotational torques may be achieved by providing visual feedback information representing the force vectors being applied to the work surface.

6.1.3 Development and Evaluation of Performance Measures for the Evaluation of Underwater Force Feedback Manipulator Systems.

- A set of performance measures for the evaluation of force feedback manipulator systems was derived and demonstrated. The two performance measures which were utilized in an experiment included:

    - Time.
    - Average of the absolute value of force (or torque) applied to the work surface.
    - Three orthogonal force vectors representing the forces applied to the work surface were recorded.
    - Two wrist joint torques were recorded.
    - The grip force was recorded.

- Three orthogonal force vectors, oriented in spherical coordinates, provided a good diagnostic measure of the operator's ability to precisely control forces.

- The two wrist torque valves recorded in the experiment allowed less precise interpretation of operator performance. A better diagnostic measure of torque control would have been the use of the three rotational torque values oriented about the axes of the force vectors recorded.

- Average applied force and time duration appear to be independent measures of performance for force feedback systems.

• Evaluation of elementary force control behavior present within complex work tasks is practical and valid. A broad range of work capability may be represented by collecting data on specific behavior elements.

6.1.4 Investigation of Design Variables in Undersea Force Feedback Manipulator Systems (Refer: Bertsche, 1975 A&B)

• A series of standard engineering test procedures were developed. These tests are applicable across a wide variety of force feedback systems and provide a basis for standardized comparisons. The two major sections of the tests are:

1. System Components Tests
2. Force Feedback Tests

The Engineering Test procedures were utilized to investigate and study selected response variables of the experimental bilateral manipulator system. Empirical data were collected on:

1. Backlash
2. Feedback Ratio
3. Rise Time (Force)
4. Settling Time (Force)
5. Overshoot (Force)
6. Force to Move
7. Compliance
8. Actuator Static and Viscous Friction

• A review of design variables applicable to force feedback manipulators was completed. Twenty-one response variables were identified which determine the fidelity of the force and position information presented to the operator. Twenty-seven design characteristics were identified which alter the hardware configuration.

- Definitions and/or testing procedures were derived for each of the twenty-one response variables and twenty-seven design characteristics.

- Five design characteristics were identified to have a critical affect on operator performance with underwater force feedback manipulators:

    1. Master controller design, position control.
    2. Master controller designs, rate control.
    3. Signal conditioning and enhancement.
    4. Feedback type.
    5. Force detection method.

- Five system response variables were identified to have a critical effect on operator performance with underwater force feedback manipulators:

    1. Backlash.
    2. Feedback ratio.
    3. Compliance.
    4. Rise time.
    5. Force to move.

6.1.5 Development of High Payload, Experimental, Manipulator Test Bed System with Data Recording Capability.

- A baseline manipulator system with visual display of force feedback information was assembled for use in experimental testing of operator performance.

- A series of improved servo control circuits were developed for the experimental manipulator system. These circuits include:

    1. Dead weight signal compensation.
    2. Motion signal compensation.
    3. Transformation of joint signals to spherical coordinate forces applied to the work surface.

- A series of data collection circuits were developed which automatically recorded the following variables:

    - Three average forces applied to the work surface.
    - Two average torques applied by the wrist joints.
    - The average grip force.
    - Four sequential time periods.

- A programmable iterative analog computer was assembled which accommodated all manipulator control circuitry, signal processing and data collection circuitry.

6.2 A VIEW OF THE FUTURE

The conduct of this research program has given the authors a unique opportunity to work with and evaluate a wide range of force feedback manipulator variables. This experience has provided a great deal of insight into both the engineering problems and the performance capability associated with such systems. While it is our desire to document actual performance differences between systems, we feel it is of value at this time to express our subjective observations in several areas. These observations are strictly limited to high payload manipulators to be deployed undersea.

In view of the increasing interest to perform work in the oceans, the work capability of undersea manipulators will need to be increased. Such a capability would be enhanced with the ability to sense and control forces applied by the manipulator. While many persons believe this is achievable only through the development of undersea bilateral manipulators, it is our observation that the technical problems of producing systems exceed the current state of the art of undersea manipulator design. We feel that a number of other system designs are, perhaps, more appropriate at this time, based on lower system costs and the ability to control force to some degree. It is of utmost importance that system designers keep

in mind that the system requirement is to control force while performing tasks; the particular method is not specified. Our experiments demonstrated that both high compliance unilateral positional systems and visual force feedback may offer economical solutions to this control problem.

In view of the experimental data documented in this report we feel that further development of high compliance unilateral position control systems will lead to the most practical solution of extending underwater work capability in the near future. While it was not possible in this experiment to document the order of magnitude improvement in control achieved by the experimental systems relative to state of the art in position and rate controlled systems, the record of arm, tool, and task damage sustained by operational rate controlled arms is an indication of their inability to precisely control force. It should be noted that the average forces recorded during this experiment were 70 to 80% less than the payload capacity of the experimental arm exerting full force. Substantial control of force was achieved with our experimental systems.

If we are asked to project future development of high compliance unilateral positional systems, we see practical application of automatic force control functions between the master controller and the slave manipulator arm. A computer might automatically limit force output of the slave arm to limits selected by the operator prior to executing a task. The operator could in effect weaken or strengthen the arm according to task requirements. Implementation of such systems in our view would be relatively inexpensive.

In the future, deployment of bilateral manipulators may become a reality. Our experience in studying these systems, however, have indicated that many questions regarding operator inter-

face problems have yet to be answered. Studies in this area are in their infancy. A research program directed at evaluation of simple bench top systems with only two or three degrees of freedom should be mandatory prior to attempting a full scale task evaluation of the type reported here. Our studies of this problem have indicated that perhaps computer simulation techniques would best supply the flexibility required to effectively study all critical design variables.

In summary we foresee that continual development of high compliance unilateral position control manipulator systems will most economically meet the immediate need for extending undersea manipulator work capability. Continuation of basic research in the area of the bilateral manipulator operator interface is required to provide future designers with specific guidelines for implementation of these systems. Relative to operational manipulators currently deployed, control of force in undersea manipulators allows the performance of closer tolerance and more delicate work.

REFERENCES

Bertsche, W.R., Pesch, A.J., Winget, C.L., "Description of an Experimental Undersea Remote Manipulator System With Force Feedback Capability", Woods Hole Oceanographic Institution Technical Memorandum No. 2-76, Nov., 1975 (A).

Bertsche, W.R., Pesch, A.J., Winget, C.L., "Investigation of Operator Performance and Related Design Variables in Undersea Force Feedback Manipulator Systems" Woods Hole Oceanographic Institution, Technical Report No. 76-47, June, 1976.

Bertsche, W.R., Pesch, A.J., Winget, C.L., "Potential Design Alternatives and Analysis of System Responses Variables, Characteristic of Undersea Manipulators with Force Feed-Back." Woods Hole Oceanographic Institution Technical Memorandum No. 1-76, Nov. 1975 (B).

Brodie, S.B., et al, "Final Report: Attached Manipulator System Design and Concept Verification for Zero-G Simulation", 1973, Martin Marietta Corp., Denver, Colo.

Flatau, C.R., et al, "Some Preliminary Correlation Between Control Modes of Manipulator Systems and Their Performance Indices", Proc. 1st National Conf. Remotely Manned Systems Manned Systems, California Institute of Technology, Pasadena, California, September 13-15, 1972, p. 189

Flatau, C.R., et al, "Design Outline for Mini-arms Based On Manipulator Technology", Massachusetts Institute of Technology, Artificial Intelligence Laboratory, Memo 300, (May 1973)

Groome, R.C., "Force Feedback Steering of a Teleoperator System", Chalres Stark Draper Laboratory, Cambridge, Mass., 1972.

Interian, A., Allen W., Kugath, D.A., "A Remote Manipulator System for Space Applications", 1969, International Symposium on Man-Machine Systems, IEEE, Cambridge, England

Nevins, J.L., Woodin, A., Whitney, D.E., "Development of Multi-Mode Remote Manipulator Systems", Annual Progress Report No. 2, Charles Stark Draper Laboratory, Cambridge, Mass., 1973.

Pesch, A.J., et al, "Operator Performance with Alternate Form of Unilateral Position Control for Undersea Manipulators", Sept. 1972 (A) Electric Boat Div., General Dynamics, Groton, Conn.

Pesch, A.J., et al, "Final Report - Operator Performance in Undersea Manipulator Systems", 1972 (B Electric Boat Div., General Dynamics, Groton, Conn.

Vertut, J., Papt, L., Rossigno, C., "Contribution to Define a Dexterity Factor for Manipulators", Proceedings of the 21st Conference on Remote Systems Technology, 1973.

APPENDIX A

SIGNAL PROCESSING FOR MANIPULATOR

CONTROL AND DATA COLLECTION

The experimental manipulator system herein described was utilized to collect operator performance data representative of a baseline undersea manipulator system with and without visual force feedback information. The general hydraulic and mechanical designs of this system were described in a previous report, Bertsche (1975A). This appendix describes signal processing details utilized in current experiments.

The experimental manipulator system was comprised of a unilateral master harness, a spherical coordinate force indicating meter display, a hydraulically powered slave arm, a data collection station, and an iterative analog computer. The interconnection of these elements are indicated in Figure A.1.

Signal processing functions which were performed by this system include:

- Generation of signals proportional to the forces applied to the working surface.
- Generation of display signals which indicated the coordinate forces and grip forces applied to the work surface.
- Provision of servo position control signals for the slave manipulator.
- Data recording during experimental tasks.

Each of these functions is discussed and associated circuitry is presented.

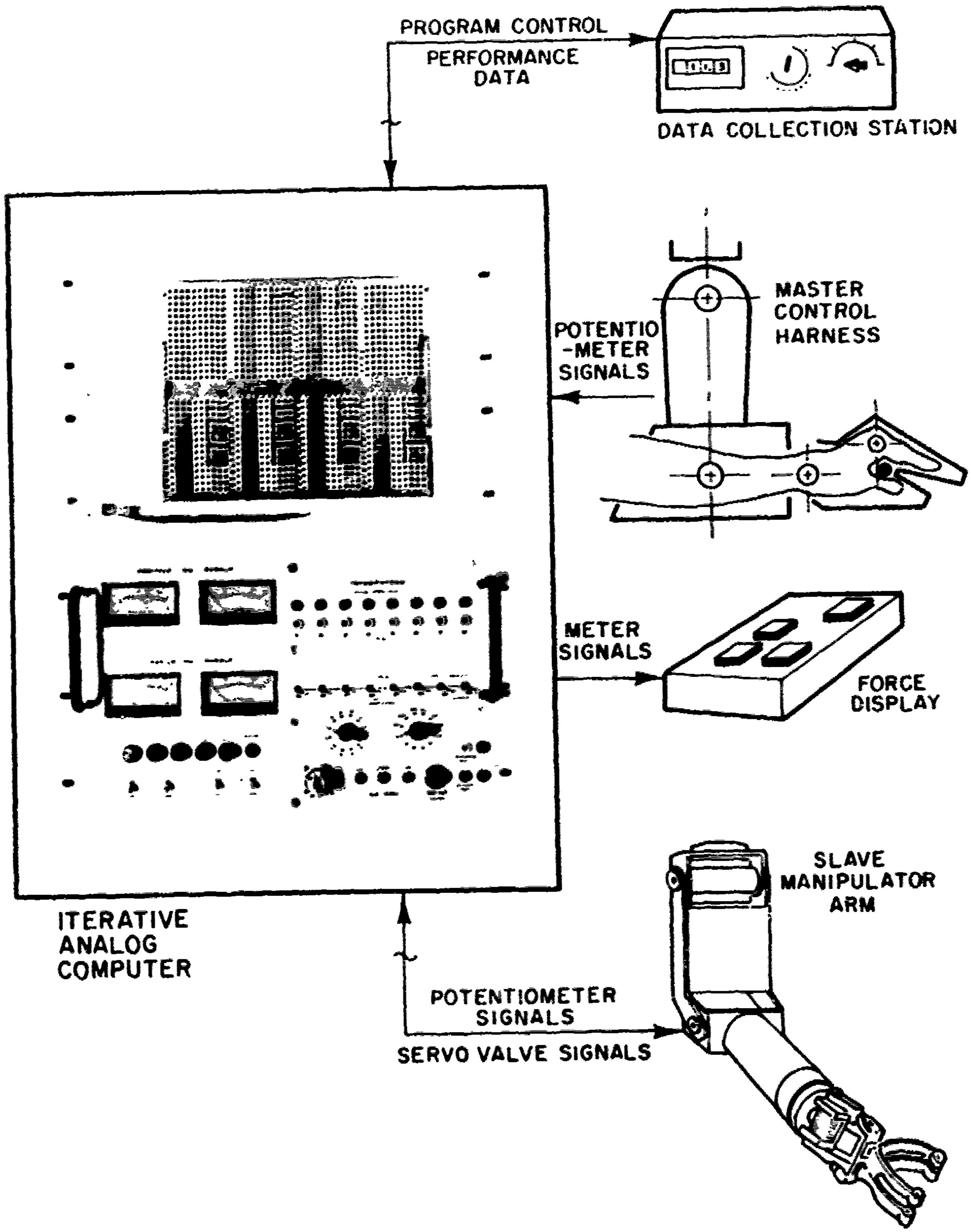


FIGURE A.1 SCHEMATIC CONFIGURATION OF THE EXPERIMENTAL MANIPULATOR SYSTEM

A.1 GENERATION OF APPLIED FORCE SIGNALS

The forces applied to the working surface by the slave manipulator were both displayed on visual meters and recorded for subsequent performance analysis. It was necessary, therefore, to generate electrical signals within the system proportional to the applied forces.

The key element in the derivation of the applied force signal was the slave servo valve. The signal to this valve was always proportional to the forces required to move the slave actuator, to carry the dead weight and to apply force to the working surface. If two of these were known, then the third i.e., applied force, might be calculated. We calculated and subtracted from the servo valve signal the dead weight and steady state motion signals. The resultant signal was proportional to the applied force plus small acceleration and static frictional forces.

The dead weight load signals were equal and opposite in direction to the moments created by the dead weight loads of the various manipulator parts. Deviation of these moments yielded the following dead weight corrections to be applied to the shoulder pivot and elbow flexion joints respectively:*

$$m_{SP}=K_1 \sin \theta_{SP} + K_2 \sin(\theta_{EB}+\theta_{SP}) \qquad (1)$$

$$m_{EB}=K_3 \sin(\theta_{EB}+\theta_{SP}) \qquad (2)$$

---

*No corrections were made to the wrist joints since they were not utilized in the force display. Load variations due to changing wrist positions were regarded as negligible since wrist positions change little in the experimental tasks. All tools were considered to weight the same.

Where

K_1, K_2, K_3 - Constants set empirically

θ_{EB} - Deflection angle of elbow

θ_{SP} - Deflection angle of shoulder pivot

The steady state motion forces were derived by assuming a linear relationship between the dynamic frictional torque of the actuator and the speed of rotation. Previous testing of the system (Bertsche 1976) had indicated this assumption to be valid.

The correction for constant speed rotation was found to be:

$$m_{\text{steady motion}} = K_4\theta \qquad (3)$$

Where

K_4 - Constant set empirically

θ_{slave} - Angluar velocity of the slave actuator

This correction was applicable to all six joints of the slave arm. It, however, did not account for the small acceleration torques and the torques required to overcome the actuator's static friction. Nevertheless, subtracting the values in equations (1), (2) and (3) from the servo valve signals yielded new signals which were very nearly equal to the applied force:

$$\begin{pmatrix}\text{Servo}\\\text{Valve}\\\text{Signal}\end{pmatrix} - \begin{pmatrix}\text{Dead}\\\text{Weight}\\\text{Torque}\end{pmatrix} - \begin{pmatrix}\text{Steady}\\\text{Motion}\\\text{Torque}\end{pmatrix} \qquad (4)$$

$$= \begin{pmatrix}\text{Applied}\\\text{Force}\end{pmatrix} + \begin{pmatrix}\text{Acceleration}\\\text{Torque}\end{pmatrix} + \begin{pmatrix}\text{Static}\\\text{Friction}\\\text{Torque}\end{pmatrix}$$

This equation provided a good approximation of applied force when the slave arm was contacting the work surface such that acceleration was small and the applied force torque was much greater than the static frictional torque. Thus:

$$\text{(Applied Force)} = \text{(Total Servo Signal)} - \text{(Dead Weight Torque)} - \text{(Steady Motion Torque)} \quad (5)$$

A.2 DISPLAY SIGNALS

The display signals of the experimental manipulator system were calculated from the applied force signals derived for the servo valves. These signals were transformed to force vectors in spherical coordinates for display on the meters. The required force vectors from an orthoganal set: normal, elevation, and azimuth force. They were parallel to the normal and tangents of a sphere at the point of contact to the work surface. The origin of the sphere was the intersection of the shoulder rotate and shoulder pivot axes. The azimuth axis was horizontal (i.e., paralled to the ground plane).

Derivation of these forces vectors yielded the following approximate relationships:*

$$F_N = .033\ (M_{EB} - .75M_{SP}) \quad (6)$$

$$F_{EL} = -.0245\ M_{SP} \quad (7)$$

$$F_{AZ} = .0185\ M_{SR} \quad (8)$$

Where

M_{EB}, M_{SP}, M_{SR} - Servo valve signals corrected for motion and dead weight.

*These relationships were valid only for a point of contact on the experimental work stand. The normal force axis was assumed to intersect the wrist pivot axis and be parallel to the wrist rotate axis. M_{EB}, M_{SP} and M_{SR} were assumed to be exceedingly greater than the wrist moments such that wrist moments did not appear in these expressions.

The force applied by the hand may be calculated exactly as

$$F_{HD} = .09\ M_{HD} \tag{9}$$

Where

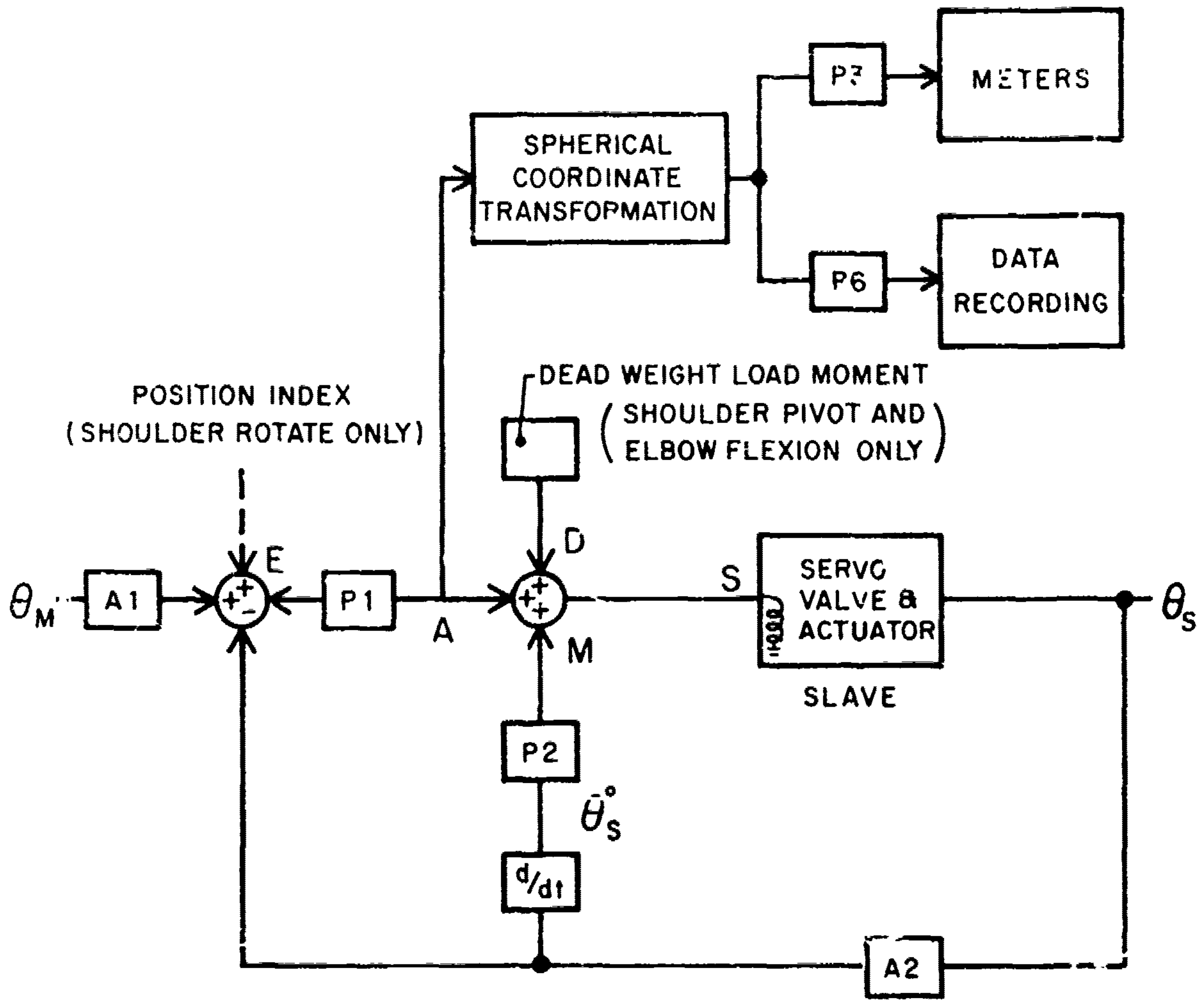
M_{HD} - Servo valve signal corrected for motion

The force signals calculated in equations (6), (7), (8) and (9) were used to drive the meter display of the force feedback system. These signals were also input to the data collection circuits for recording during the performance of experimental tasks.

A.3 SERVO POSITION CONTROL SIGNALS

The position control loop of each manipulator joint provided a negative feedback position error signal and a positive feedback rate signal. The feedback loop utilized for all six joints of the slave manipulator is illustrated in Figure A.2. This loop was arranged so that the signal representing applied force was accessible for display and data recording. The circuit was designed to allow adjustment of loop gains without disturbing calibration of the meter and data collection circuits.

The position of the positive rate feedback path in the control loop provided for both the correction of steady motion forces and an increase in the time response of the system with a low loop gain. (Allowing high compliance). Figure A.3.1 illustrates typical positional time responses of the elbow flexion joint. The response was recorded with and without positive rate feedback. These curves indicated that positive rate feedback reduces the rise time from .7 sec. to .4 sec. Figure A.3.2 illustrates that for the same joint under constant



θ_M = MASTER POSITION

θ_S = SLAVE POSITION

E = $\theta_M - \theta_S$

A = [APPLIED FORCE TORQUE] + [ACCELERATION TORQUE] + [STATIC FRICTIONAL TORQUE] ≅ [APPLIED FORCE TORQUE]

D = DEAD WEIGHT LOAD MOMENT

M = STEADY MOTION TORQUE

S = SERVO SIGNAL = [APPLIED FORCE TORQUE] + [DEAD WEIGHT LOAD MOMENT] + [MOTION FORCES] = [HYDRAULIC FLUID FLOW]

A_1 A_2, P_1, P_2, P_3, P_6 = SYSTEM GAINS

FIGURE A.2 CONTROL DIAGRAM, SLAVE MANIPULATOR ARM

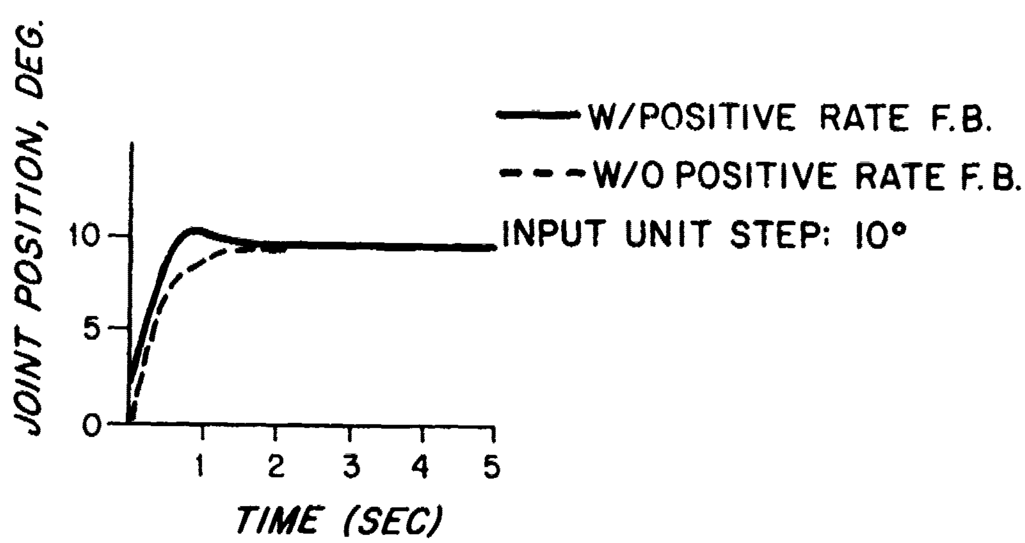


FIGURE A.3.1 POSITIONAL TIME RESPONSE TO UNIT STEP INPUT

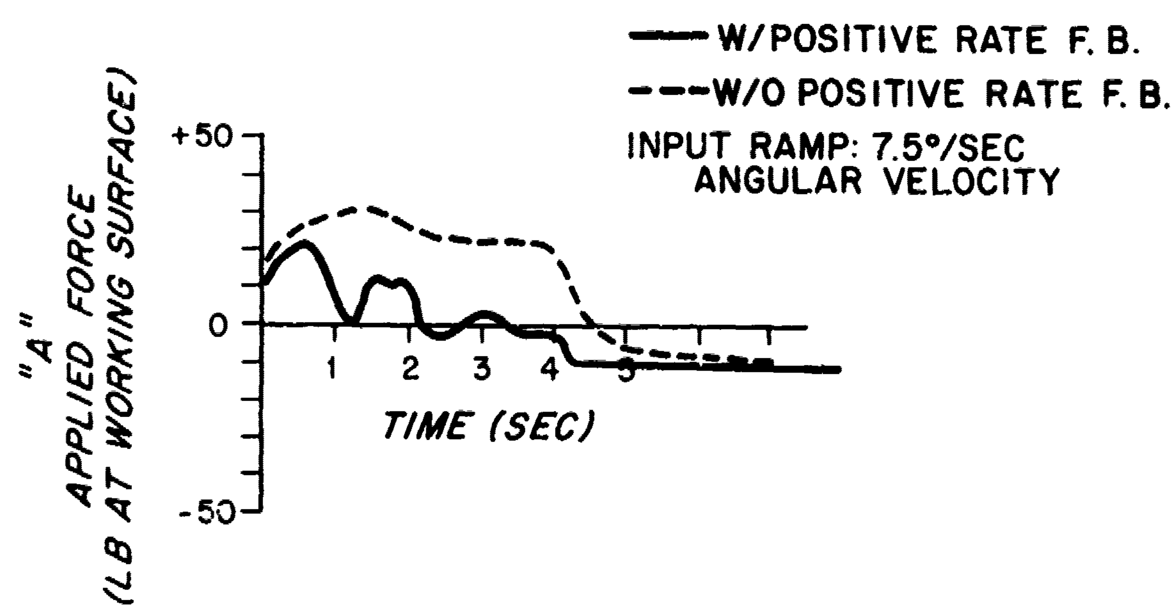


FIGURE A.3.2 TIME RESPONSE OF APPLIED FORCE SIGNAL TO A RAMP INPUT

<u>FIGURE A.3</u> EFFECTS OF POSITIVE RATE FEEDBACK ON TIME RESPONSE OF THE SLAVE MANIPULATOR

motion positive rate feedback also holds the applied force torque signal near zero while the system is in motion. The offset of this signal before and after motion was due to the actuator static friction.

A.4 DATA COLLECTION METHODS

Two types of data were recorded during every experimental task, time and the integral sum of the absolute value of selected forces and torques. Mathematically, these measures are represented as:

T - Time Period (10)

$\int^{T} |F| \, dt$ - Integral over period T of the absolute value of the applied force (equivalent to work) (11)

The measures in equations (10) and (11) were combined during post experimental analysis to formulate the average forces applied to the working surface during various tasks segments. This is represented as:

$\frac{1}{T}\int^{T} |F| \, dt$ - Average absolute force (or torque) applied during period T (12)

Electronic analog integrators were utilized to record all data. The absolute values of the force signals were integrated directly during each selected time period. A measure of the time period was obtained by integrating a constant reference voltage. The integral of a constant was proportional to time:

$$\int^{T} K \, dt = Kt \Big|_0^T = KT \qquad (13)$$

K - Constant

T - Time period of the integration

Four time periods and six absolute force integrals for each of two time periods were recorded for every experimental task, i.e., 16 data points. These are listed in Table A.1.

Automatic control of the data recording integrators was provided by the iterative design of the analog computer. Integrators were automatically reset, set to operate, and set to hold as a function of a program sequence switch located at the data collection station, Figure A.4. At the completion of a task, all integrators were left in the hold mode. Their output voltages were scanned by another switch located at the experimenter's station. Integrator voltages were copied by the observer and input to a digital computer for statistical analysis.

A.5 ELECTRONIC CIRCUITRY

All of the control, display, and compensation signals for the manipulator system were generated on an iterative analog computer which was custom built for this research program.

The computer consists of:

1	Patch Panel (interchangeable)
64	Programmable Summing Amplifiers
48	Programmable Integrators (Controllable in groups of six)
24	Programmable Single Pole Double Throw Relays
120	Programmable Potentiometers

The supply voltages for the computer are $\pm$ 15 volt D.C. Figure A.5 represents the typical circuitry utilized to control each joint of the system. The sympology was typical of that utilized in analog computer programming.

T_1	Time Period
T_2	Time Period
T_3	Time Period
T_4	Time Period
$\int^{T_3} \lvert M_{WP} \rvert dt$	Integral over time period T_3
$\int^{T_3} \lvert M_{WR} \rvert dt$	Integral over time period T_3
$\int^{T_3} \lvert F_{EL} \rvert dt$	Integral over time period T_3
$\int^{T_3} \lvert F_{AZ} \rvert dt$	Integral over time period T_3
$\int^{T_3} \lvert F_{N} \rvert dt$	Integral over time period T_3
$\int^{T_3} \lvert F_{HD} \rvert dt$	Integral over time period T_3
$\int^{T_4} \lvert M_{WP} \rvert dt$	Integral over time period T_4
$\int^{T_4} \lvert M_{WR} \rvert dt$	Integral over time period T_4
$\int^{T_4} \lvert F_{EL} \rvert dt$	Integral over time period T_4
$\int^{T_4} \lvert F_{AZ} \rvert dt$	Integral over time period T_4
$\int^{T_4} \lvert F_{N} \rvert dt$	Integral over time period T_4
$\int^{T_4} \lvert F_{HD} \rvert dt$	Integral over time period T_4

TABLE A.1 RECORDED DATA POINTS

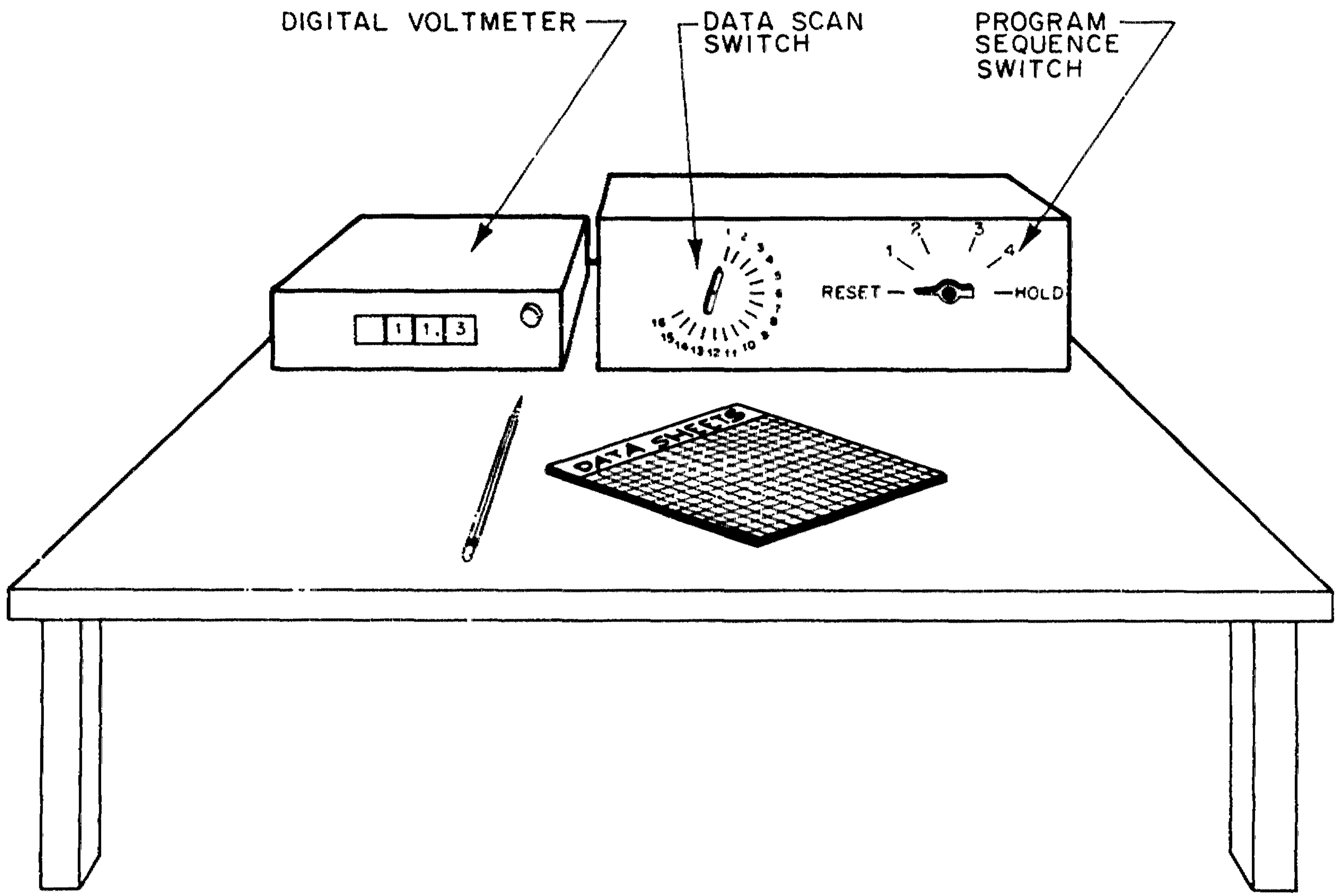


FIGURE A.4 CONTROL PANEL AT DATA COLLECTION STATION

Operation of this circuit is as follows:

- The buffer amplifiers A1 and A2 provided signal gain for equivalent scaling of θ_m and θ_S.
- The potentiometer P1 was the loop gain for the negative position error feedback, $\theta_m - \theta_S$.
- The potentiometer P2 provided loop gain for the positive rate feedback, θ_S.
- Amplifiers A4 and A5 were summers which were utilized to drive the servo valve in a push-pull manner.
- The 2.2K series resisters limited currents in the servo coils to 4 ma. maximum.
- The output of amplifier A4 was approximately equal to the applied force.
- Potentiometer P3 and P6 provided the proper scaling and transform signals into spherical coordinate forces for display on the meter array and for recording on the data collection integrators, A9 and A10.
- Integrators A9 and A10 record data and were controlled by the program sequencing switch via logic input terminals.
- Integrator A9 operated only during time period T_3.
- Integrator A10 operated only during time period T_4.

The schematic diagrams and gain settings for all six manipulator joints follows in Figures A.6 to A.11. Also, presented are circuit diagrams for the timing circuits, program sequencing switch, data scanning switch, amplifier configurations, integrator configurations, potentiometer circuits and relay circuits, Figure A.12 to A.18.

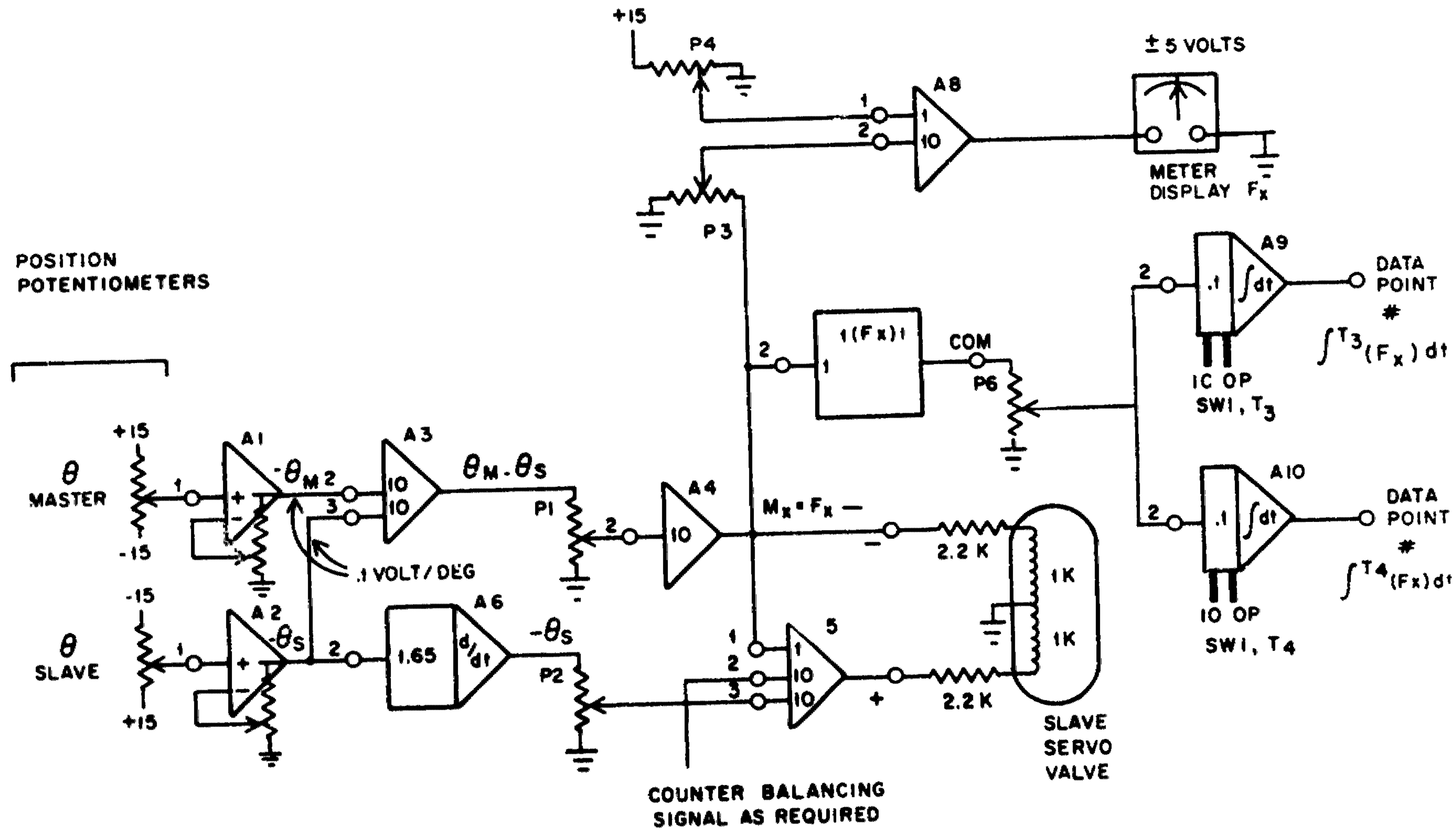


FIGURE A.5 CIRCUIT DIAGRAM, TYPICAL JOINT CIRCUIT

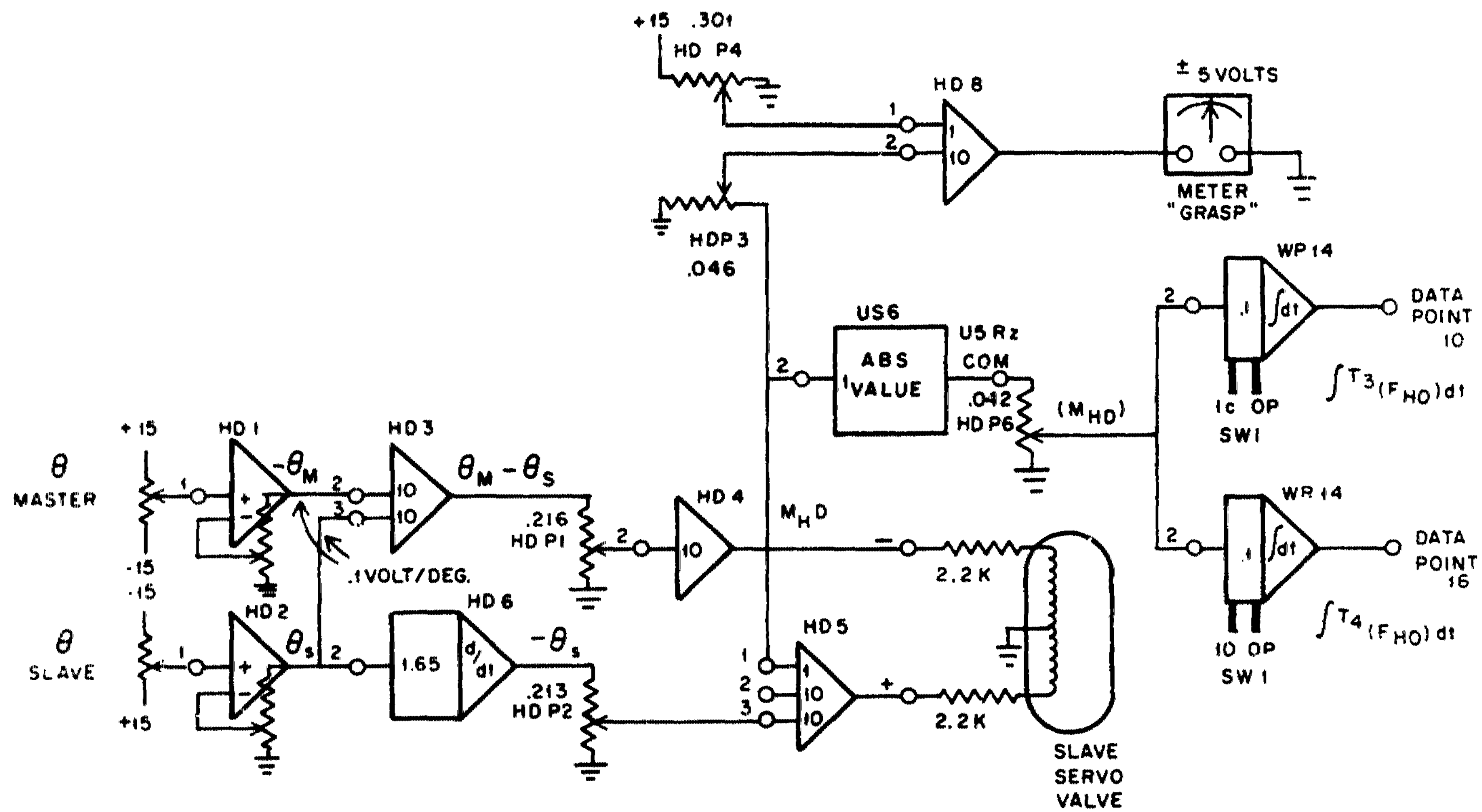


FIGURE A.6 CIRCUIT DIAGRAM, HAND JOINT

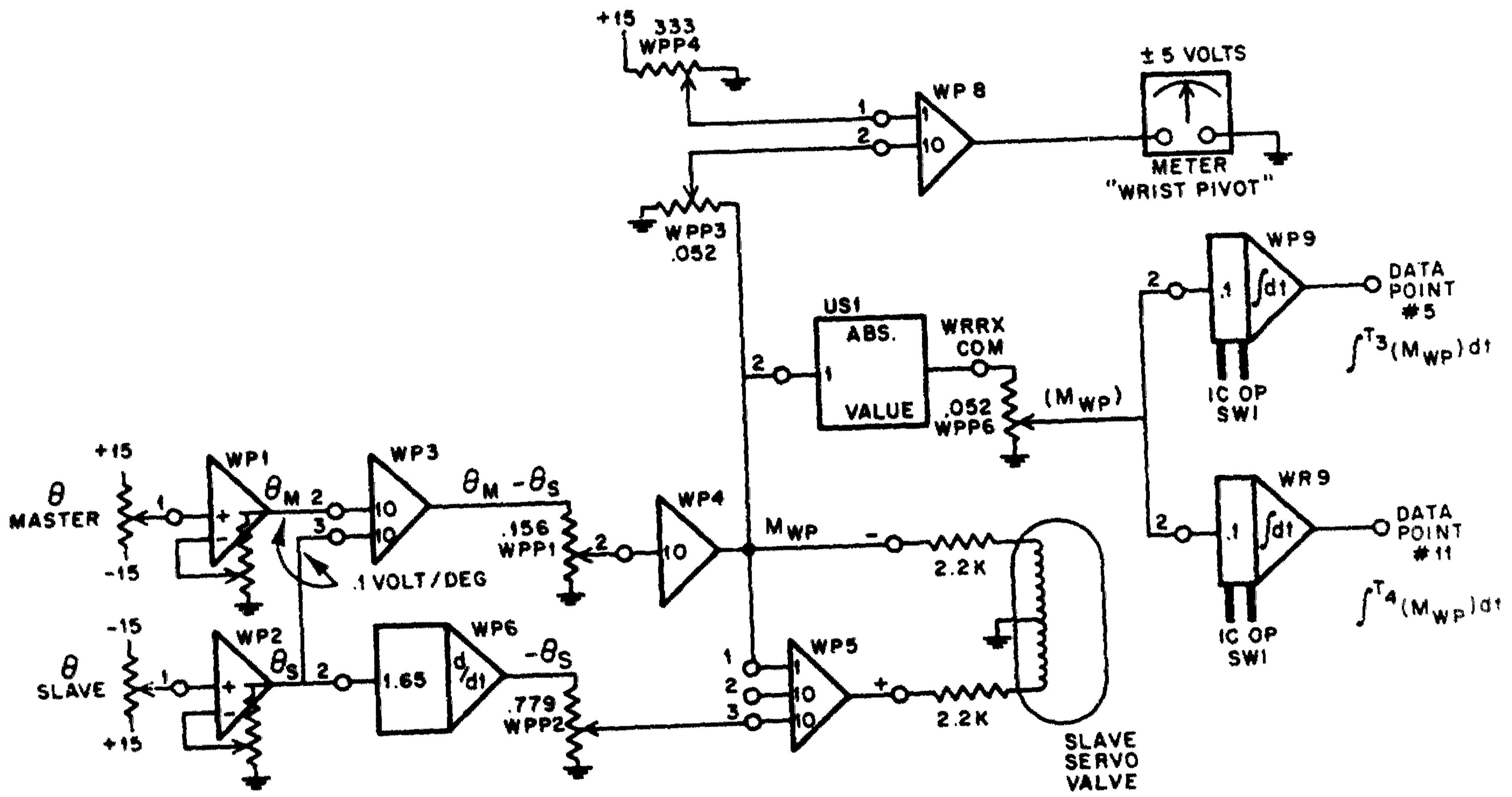


FIGURE A.7 CIRCUIT DIAGRAM, WRIST PIVOT

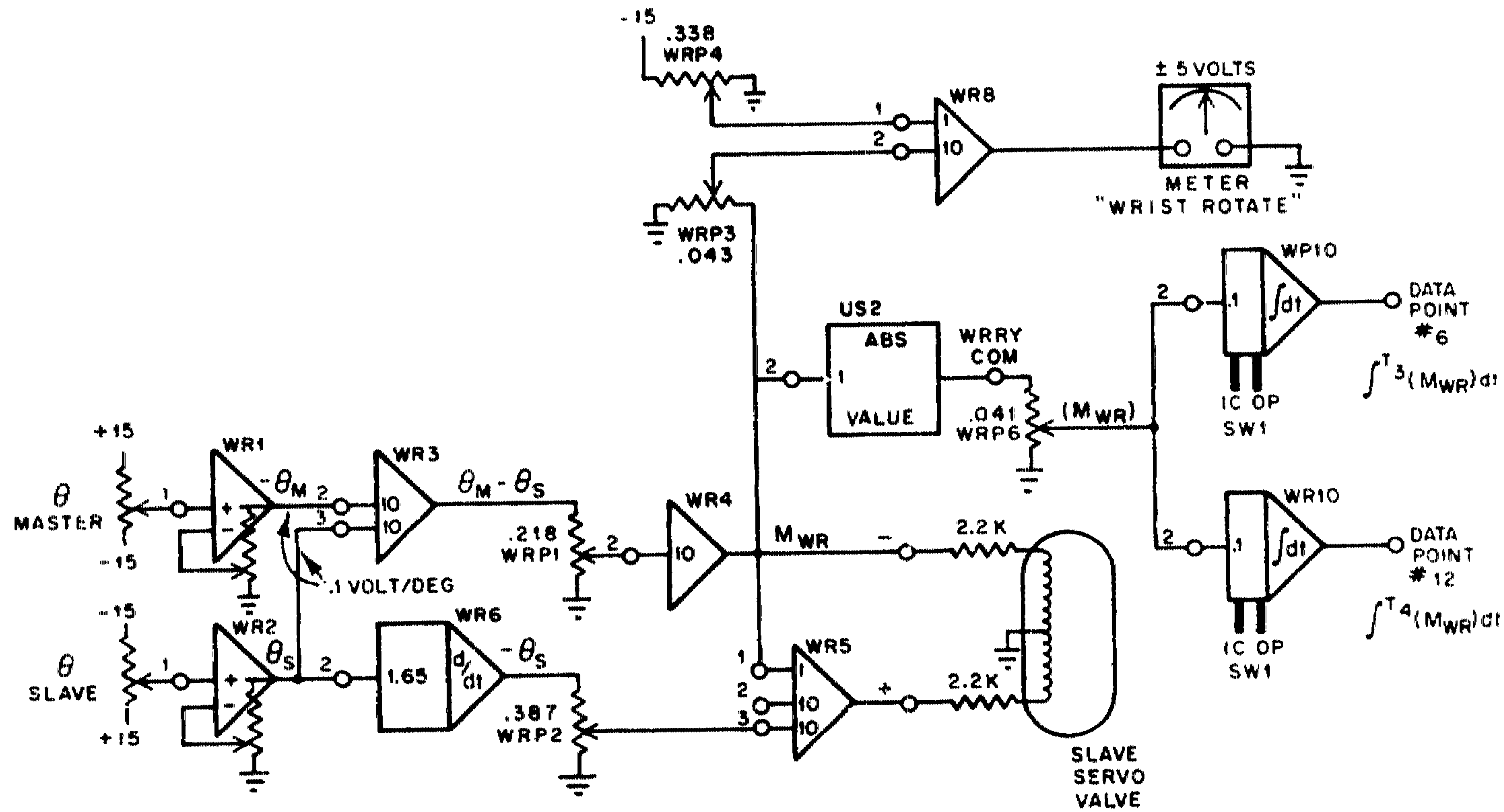


FIGURE A.8 CIRCUIT DIAGRAM, WRIST ROTATE

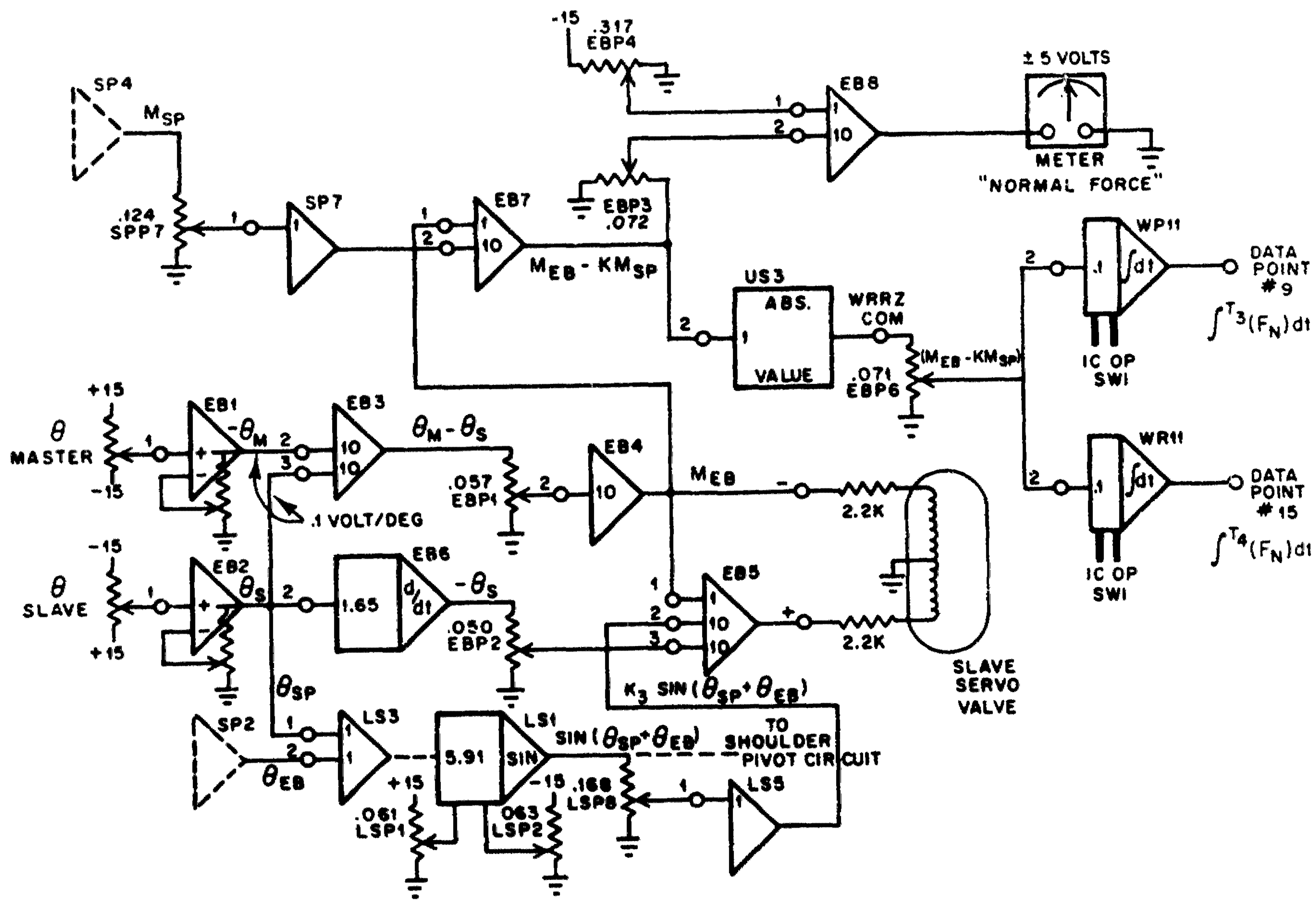


FIGURE A.9 CIRCUIT DIAGRAM, ELBOW FLEXION

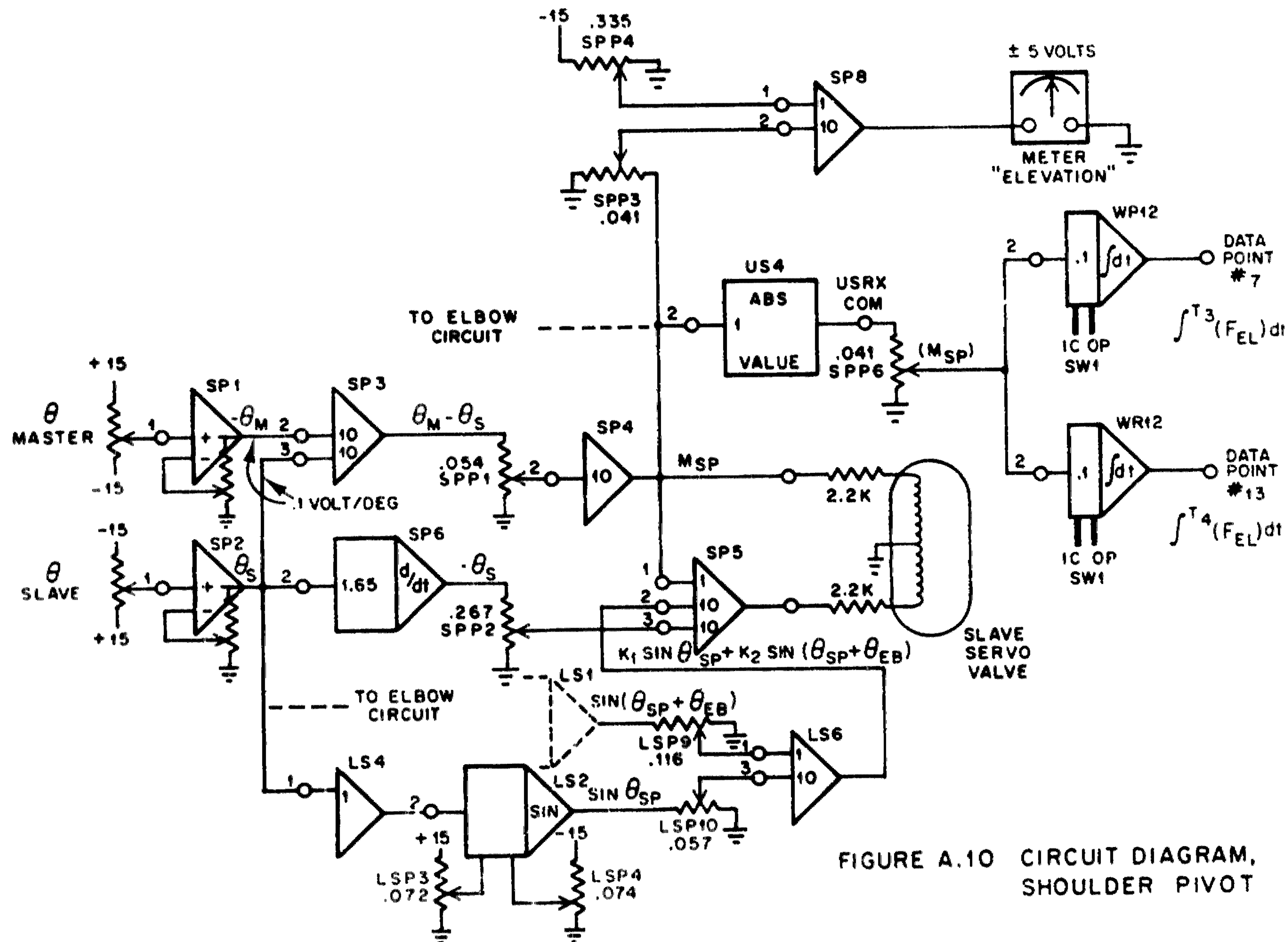


FIGURE A.10 CIRCUIT DIAGRAM, SHOULDER PIVOT

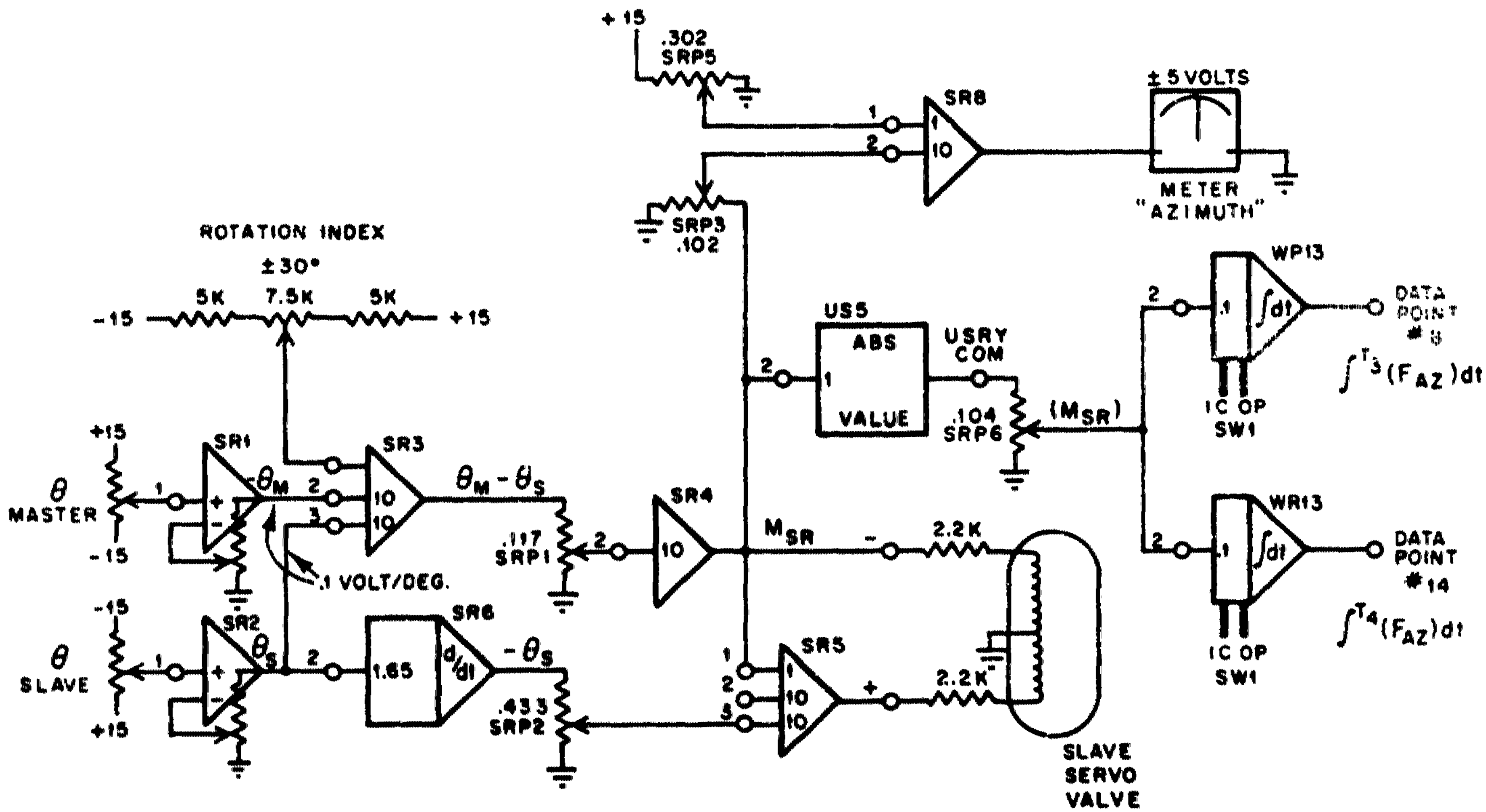


FIGURE A.11 CIRCUIT DIAGRAM, SHOULDER ROTATE

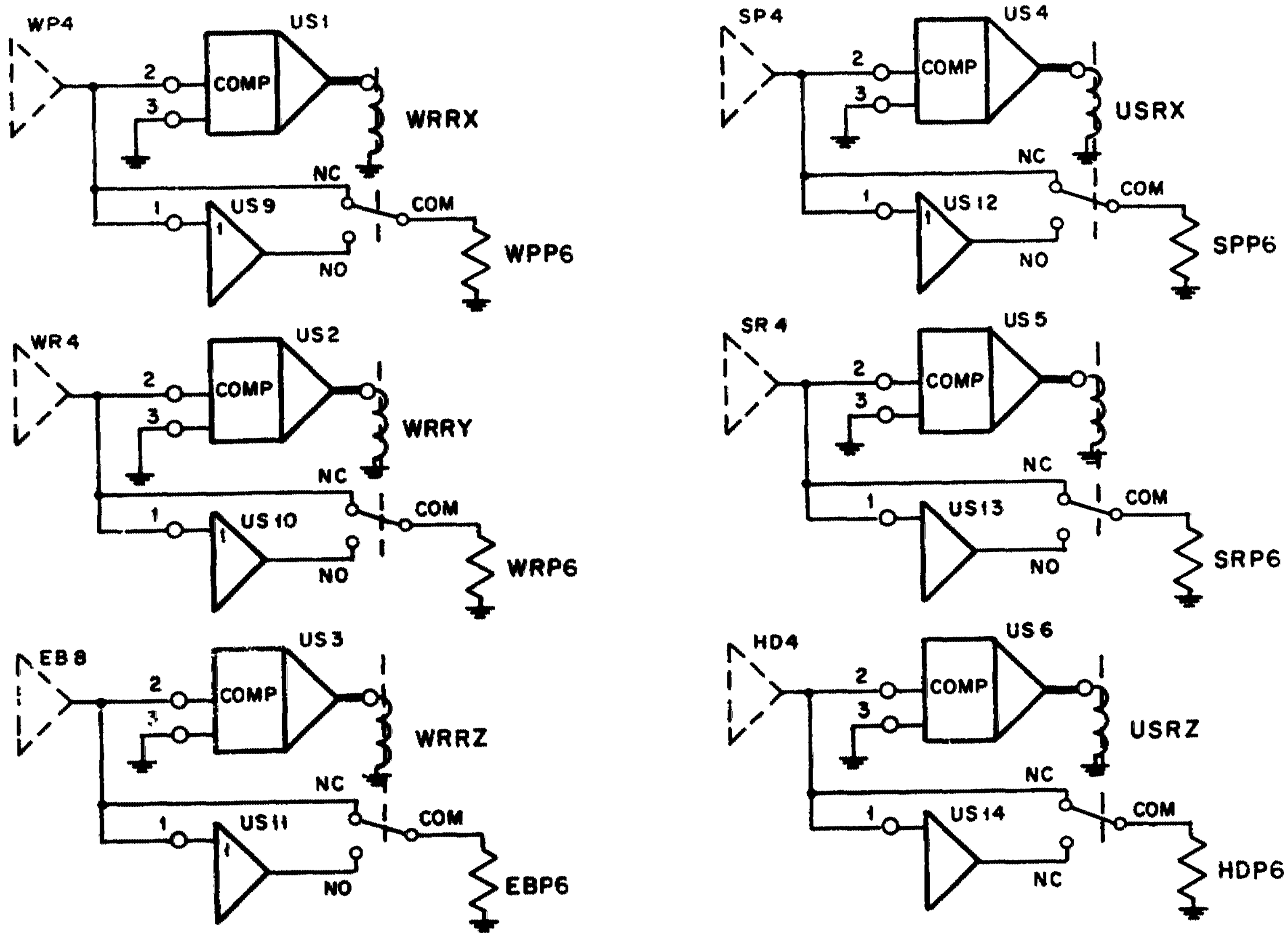


FIGURE A.12 SCHEMATIC DIAGRAM, ABSOLUTE VALUE CIRCUITS

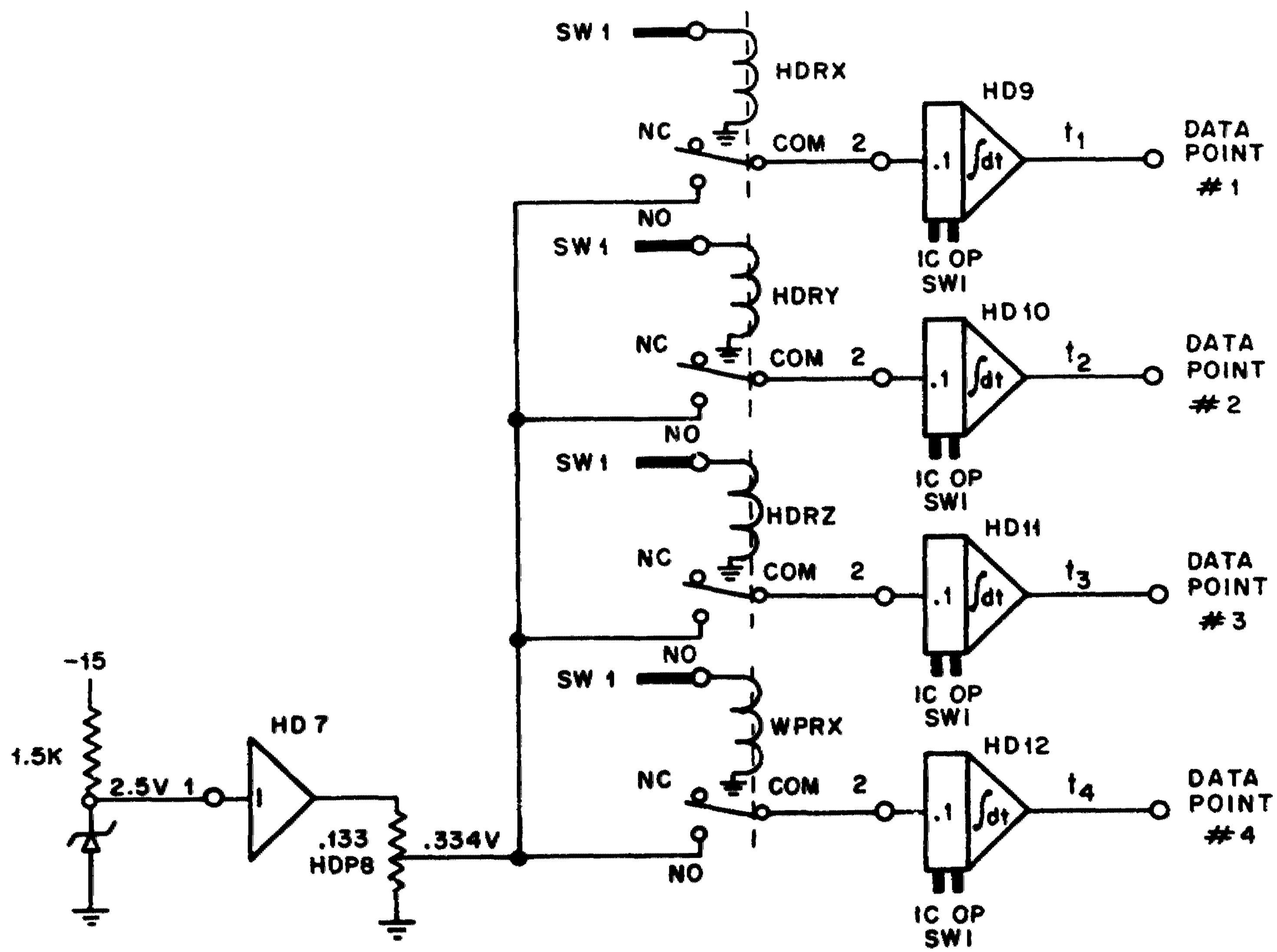


FIGURE A.13 SCHEMATIC DIAGRAM TIMING CIRCUITS

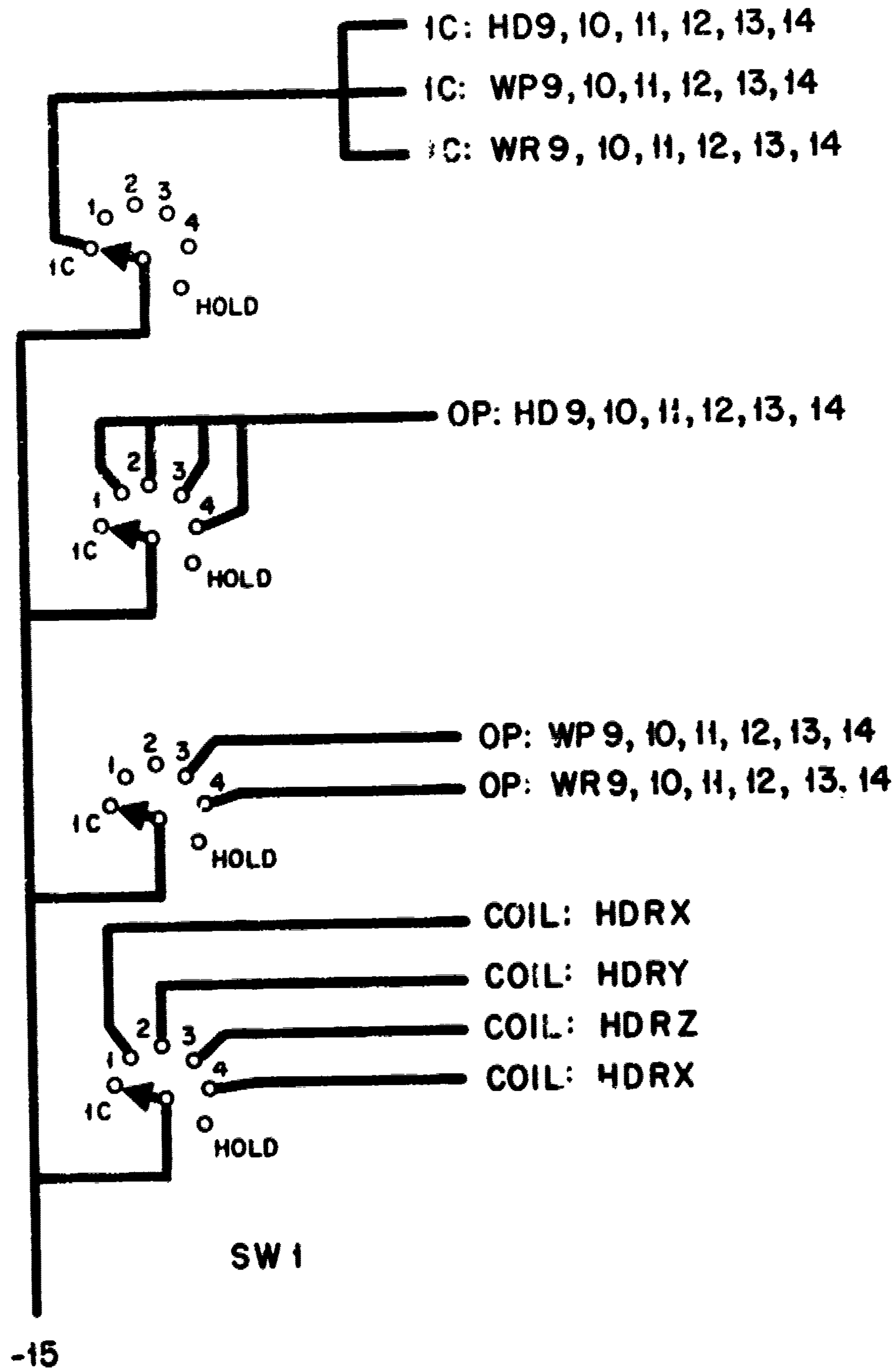


FIGURE A.14 CIRCUIT DIAGRAM, PROGRAM SEQUENCING SWITCH

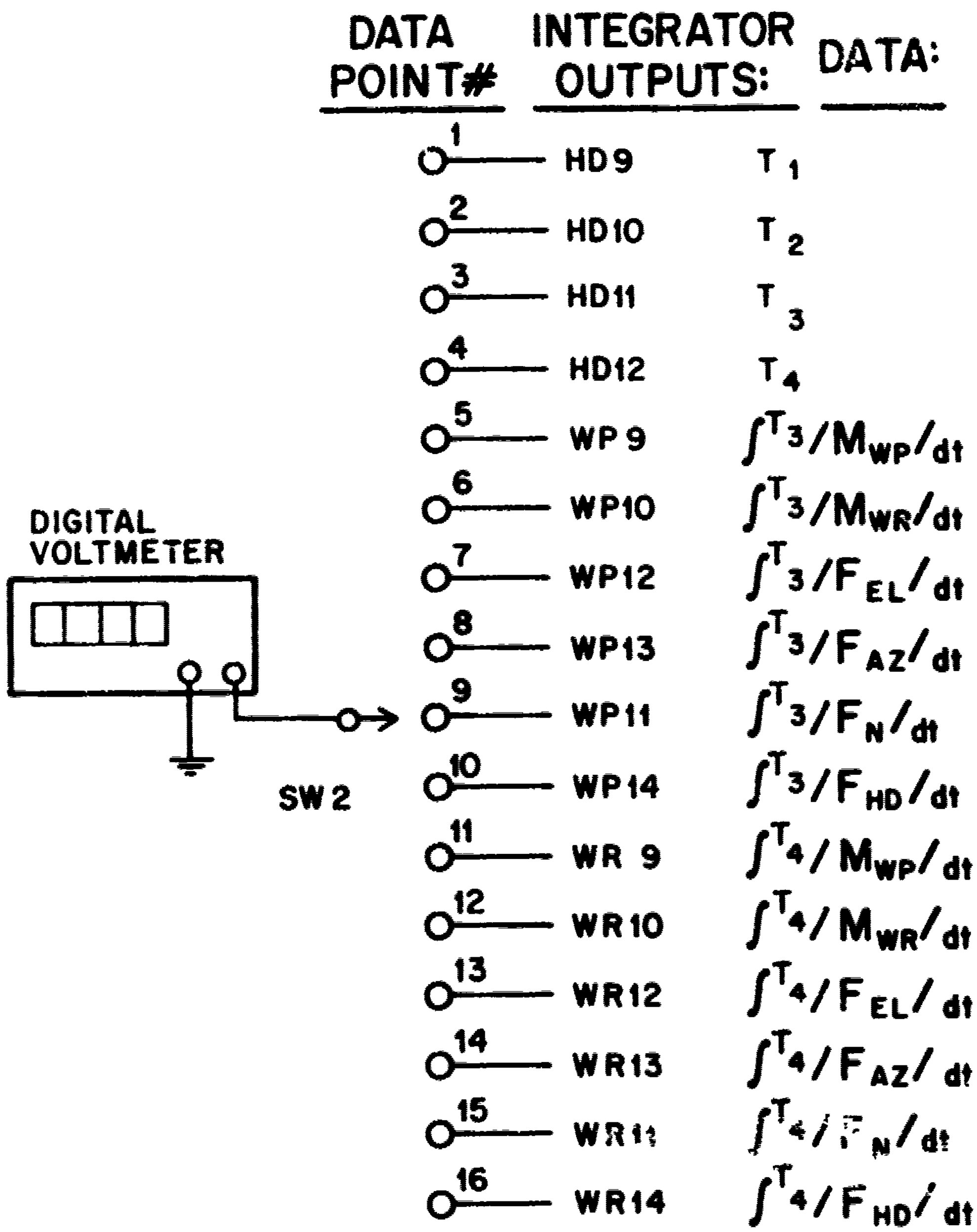


FIGURE A.15 CIRCUIT DIAGRAM DATA SCAN SWITCH

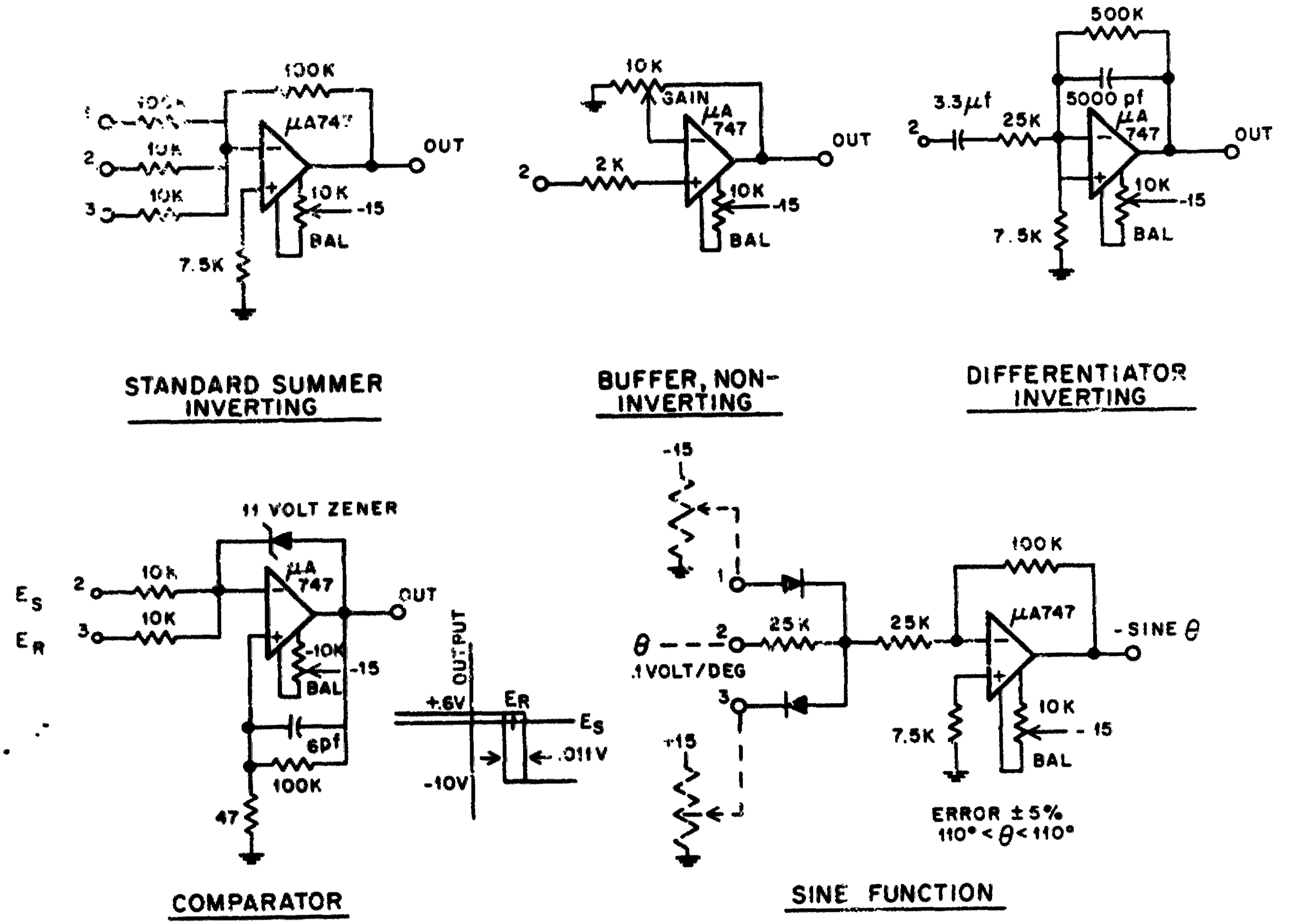
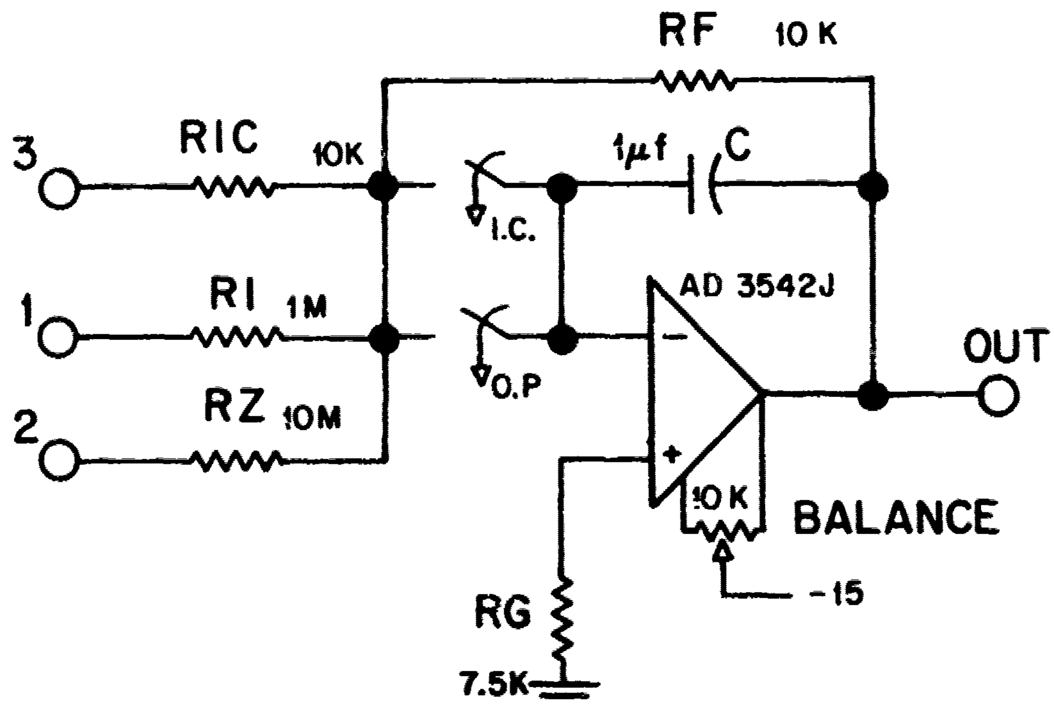
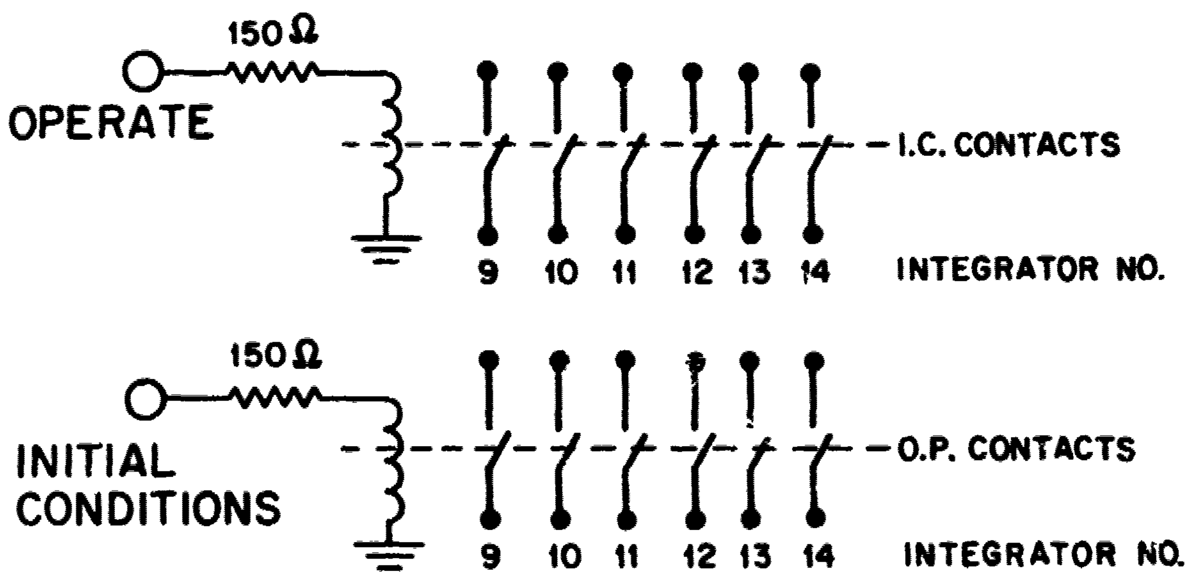


FIGURE A.16 CIRCUIT DIAGRAM OF OPERATIONAL AMPLIFIERS



INTEGRATOR RELAYS CONTROL SIX INTEGRATORS SIMULTANEOUSLY



6 PST RELAYS CLARE NO. MRB6A12
OPERATE ON 9VDC MINIMUM

FIGURE A.17 CIRCUIT DIAGRAM, INVERTING INTEGRATOR

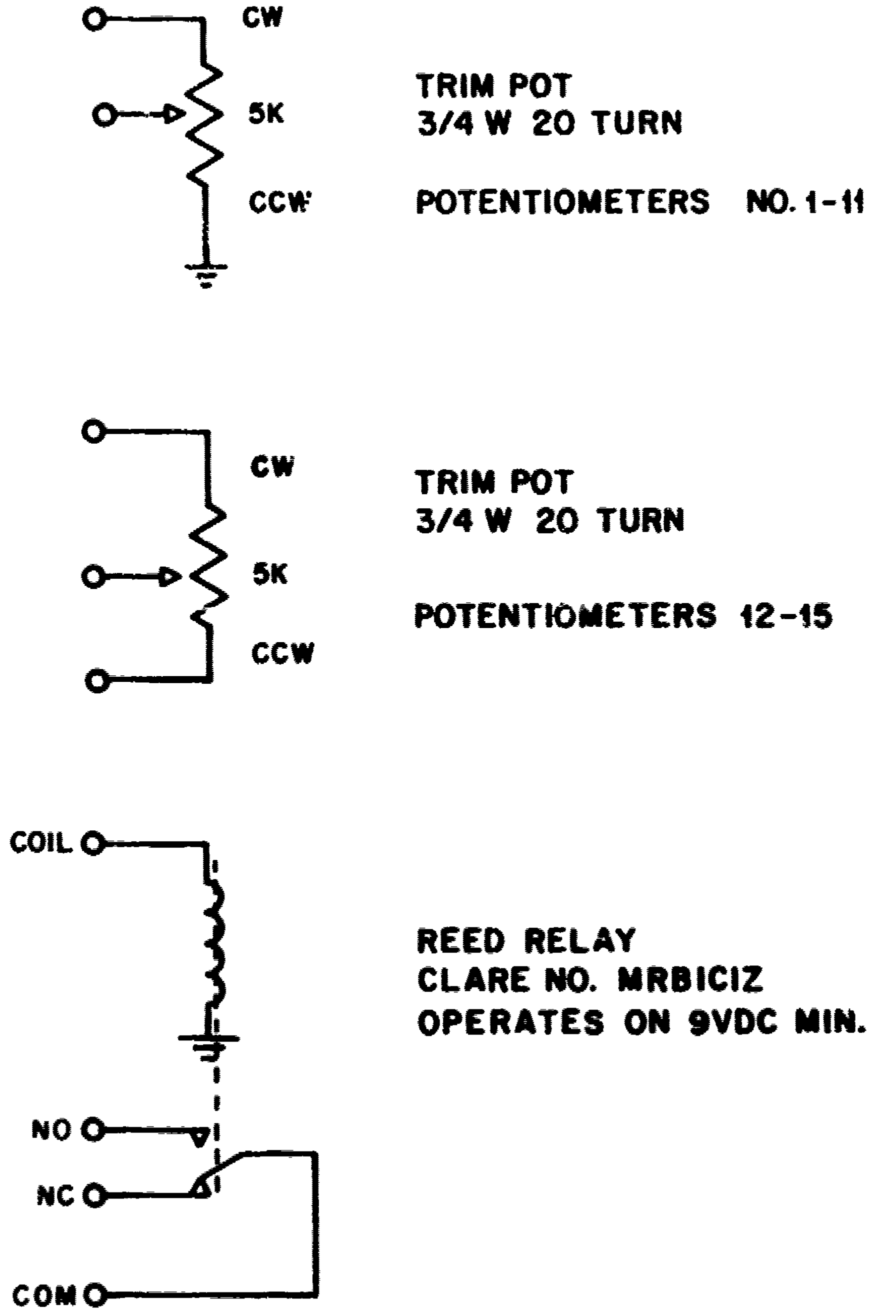


FIGURE A.18 CIRCUIT DIAGRAMS, POTENTIOMETERS AND RELAYS

APPENDIX B

STATISTICAL ANALYSIS SUMMARY

This appendix contains the statistical analysis summary, including the analysis of variance summary tables.

The following abbreviations are used in the body of the tables in this appendix.

S = Subjects
C = Manipulator Control Systems
T = Trials
P = Probability
Tk = Tasks

B.1 INDEX TO ANALYSIS OF VARIANCE SUMMARY TABLES

TABLE	TASK	ELEMENT	FIGURE
B1.1	Core Tube @ 45°	Elevation - Insert	4.2.1
B1.2	Core Tube @ 45°	Elevation - Withdraw	4.2.1
B1.3	Core Tube @ 45°	Azimuth - Insert	4.2.2
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B1.6	Core Tube @ 45°	Normal - Withdraw	4.2.3
B1.7	Core Tube @ 45°	Wr. Pivot - Insert	4.2.4
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B1.10	Core Tube @ 45°	Wr. Rotate - Withdraw	4.2.5
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B1.12	Core Tube @ 45°	Resultant - Withdraw	4.3.1
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TABLE	TASK	ELEMENT	FIGURE
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B2.8	Core Tube @ 90°	Wr. Pivot - Withdraw	4.4.4
B2.9	Core Tube @ 90°	Wr. Rotate - Insert	4.4.5
B2.10	Core Tube @ 90°	Wr. Rotate - Withdraw	4.4.5
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B4.1	Surface Following	Elevation - Downward	4.7.1
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B4.3	Surface Following	Azimuth - Downward	4.7.2
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B4.5	Surface Following	Normal - Downward	4.7.3
B4.6	Surface Following	Normal - Upward	4.7.3
B4.7	Surface Following	Wr. Pivot - Downward	4.7.4
B4.8	Surface Following	Wr. Pivot - Upward	4.7.4
B4.9	Surface Following	Wr. Rotate - Downward	4.7.5
B4.10	Surface Following	Wr. Rotate - Upward	4.7.5
B4.11	Surface Following	Resultant - Downward	4.8.1
B4.12	Surface Following	Resultant - Upward	4.8.1
B4.13	Surface Following	Time - Downward	4.8.2
B4.14	Surface Following	Time - Upward	4.8.2
B5.1	Drilling	Elevation - Drill	4.9.1
B5.2	Drilling	Elevation - Withdraw	4.9.1
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TABLE	TASK	ELEMENT	FIGURE
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B5.6	Drilling	Normal - Withdraw	4.9.3
B5.7	Drilling	Wr. Pivot - Drill	4.9.4
B5.8	Drilling	Wr. Pivot - Withdraw	4.9.4
B5.9	Drilling	Wr. Rotate - Drill	4.9.5
B5.10	Drilling	Wr. Rotate - Withdraw	4.9.5
B5.11	Drilling	Resultant - Drill	4.10.1
B5.12	Drilling	Resultant - Withdraw	4.10.1
B5.13	Drilling	Time - Drill	4.10.2
B5.14	Drilling	Time - Withdraw	4.10.2
B6.1	All Tasks	Learning	4.1

TABLE B1.1

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	100.36	1	100.36	3.02	-
S	2,052.86	5	410.57	12.37	.01
T	470.70	9	52.30	1.58	-
CS	448.77	5	89.75	2.70	.05
CT	430.49	9	47.82	1.44	-
ST	2,386.17	45	53.03	1.60	-
CST	1,493.26	45	33.18		

System	Mean
Baseline	21.58
Baseline with meters	19.75

TABLE B1.2

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	6,188.95	1	6,188.95	4.78	.05
S	9,492.80	5	1,898.56	1.47	-
T	9,468.08	9	1,052.01	.81	-
CS	7,794.65	5	1,558.93	1.20	-
CT	11,845.41	9	1,316.16	1.02	-
ST	60,836.34	45	1,351.92	1.04	-
CST	58,258.39	45	1,294.63		

System	Mean
Baseline	23.30
Baseline with Meters	8.94

TABLE B1.3

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	8,387.77	1	8,387.77	15.17	.01
S	18,026.13	5	3,605.23	6.52	.01
T	5,616.22	9	624.02	1.13	-
CS	10,355.14	5	2,071.03	3.74	.01
CT	7,351.42	9	816.82	1.48	-
ST	26,682.98	45	592.96	1.07	-
CST	24,888.52	45	553.09		

System	Mean
Baseline	40.04
Baseline with meters	23.32

TABLE B1.4

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	33,399.59	1	33,399.59	74.20	.01
S	11,180.58	5	2,236.12	4.97	.01
T	2,726.54	9	302.95	.67	-
CS	8,954.00	5	1,790.80	3.98	.01
CT	5,008.50	9	556.50	1.24	-
ST	22,474.08	45	499.42	1.11	-
CST	20,255.27	45	450.13		

System	Mean
Baseline	44.06
Baseline with meters	10.07

TABLE B1.5

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	491.64	1	491.64	1.38	-
S	29,264.79	5	5,852.96	16.30	.01
T	6,872.24	9	763.58	2.14	.05
CS	2,020.81	5	404.16	1.13	-
CT	5,184.80	9	576.09	1.60	-
ST	23,231.79	45	516.26	1.45	-
CST	16,065.96	45	357.02		

System	Mean
Baseline	31.99
Baseline with meters	27.95

TABLE B1.6

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	17,662.24	1	17,662.24	74.67	.01
S	7,402.49	5	1,480.50	6.26	.01
T	1,555.15	9	172.79	.73	-
CS	1,941.79	5	388.36	1.64	-
CT	4,032.73	9	448.08	1.89	-
ST	13,558.51	45	300.86	1.27	-
CST	10,644.75	45	236.55		

System	Mean
Baseline	45.31
Baseline with meters	21.04

T·BLE B1.7

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	4.52	1	4.52	.02	-
S	9,046.64	5	1,809.33	9.81	.01
T	1,218.10	9	135.34	.73	-
CS	2,200.98	5	440.20	2.39	.05
CT	1,228.70	9	136.52	.74	-
ST	9,988.10	45	221.96	1.20	-
CST	8,295.47	45	184.34		

System	Mean
Baseline	6.54
Baseline with meters	6.93

TABLE B1.8

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	5.68	1	5.68	.02	-
S	18,366.16	5	3,673.23	13.24	.01
T	845.79	9	93.98	.34	-
CS	6,336.01	5	1,267.20	4.57	.01
CT	1,742.27	9	193.59	.70	-
ST	13,409.80	45	298.00	1.07	-
CST	12,488.80	45	277.53		

System	Mean
Baseline	27.45
Baseline with meters	27.89

TABLE B1.9

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	0.42	1	0.92	.01	-
S	2,219.96	5	443.99	6.40	.01
T	642.33	9	71.37	1.03	-
CS	85.38	5	17.08	.25	-
CT	1,098.64	9	122.07	1.76	-
ST	2,745.61	45	61.01	.88	-
CST	3,120.51	45	69.34		

System	Mean
Baseline	13.32
Baseline with meters	13.14

TABLE B1.10

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	2,357.96	1	2,357.96	23.74	.01
S	3,936.83	5	787.37	7.93	.01
T	884.78	9	98.31	.99	-
CS	2,020.80	5	404.16	4.07	.01
CT	1,758.03	9	195.34	1.97	-
ST	4,450.98	45	98.91	1.00	-
CST	4,470.50	45	99.34		

System	Mean
Baseline	26.75
Baseline with meters	17.88

TABLE B1.11

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	7,214.79	1	7,214.79	12.05	.01
S	37,083.40	5	7,416.68	12.39	.01
T	10,659.91	9	1,184.43	1.98	-
CS	7,421.10	5	1,484.22	2.48	.05
CT	11,325.39	9	1,258.38	2.10	.05
ST	42,368.14	45	941.51	1.57	-
CST	26,940.69	45	598.68		

System	Mean
Baseline	57.65
Baseline with meters	42.15

TABLE B1.12

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	68,623.60	1	68,623.60	57.18	.01
S	31,347.84	5	6,269.57	5.22	.01
T	8,432.83	9	936.98	.78	-
CS	19,378.11	5	3,875.62	3.23	.05
CT	17,824.35	9	1,980.48	1.65	-
ST	59,659.46	45	1,325.77	1.10	-
CST	54,001.86	45	1,200.04		

System	Mean
Baseline	72.28
Baseline with meters	24.45

TABLE B1.13

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	6,413.65	1	6,413.65	39.21	.01
S	3,878.96	5	775.79	4.74	.01
T	3,167.60	9	351.96	2.15	.05
CS	1,218.48	5	243.70	1.49	-
CT	2,698.83	9	299.87	1.83	-
ST	6,887.93	45	153.07	.94	-
CST	7,360.17	45	163.56		

System	Mean
Baseline	14.06
Baseline with meters	28.68

TABLE B1.14

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	6,242.56	1	6,242.56	21.14	.01
S	6,483.24	5	1,296.65	4.39	.01
T	2,374.19	9	263.80	.89	-
CS	2,976.33	5	595.27	2.02	-
CT	2,457.84	9	273.09	.92	-
ST	16,025.55	45	356.12	1.21	-
CST	13,285.54	45	295.23		

System	Mean
Baseline	10.53
Baseline with meters	24.96

TABLE B2.1

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	242.09	1	242.09	5.35	.05
S	2,285.27	5	457.05	10.09	.01
T	856.00	9	95.11	2.10	.05
CS	249.00	5	49.80	1.10	-
CT	534.18	9	59.35	1.31	-
ST	2,414.27	45	53.65	1.18	-
CST	2,037.60	45	45.28		

System	Mean
Baseline	25.26
Baseline with meters	22.42

TABLE B2.2

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	241.04	1	241.04	5.08	.05
S	3,183.35	5	636.67	13.42	.01
T	453.54	9	50.39	1.06	-
CS	99.37	5	19.87	.42	-
CT	674.99	9	75.00	1.58	-
ST	2,645.34	45	58.79	1.24	-
CST	2,134.77	45	47.44		

System	Mean
Baseline	16.24
Baseline with meters	13.40

TABLE B2.3

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	581.05	1	581.05	3.65	-
S	3,771.16	5	754.23	4.74	.01
T	1,627.26	9	180.81	1.14	-
CS	6,203.53	5	1,240.71	7.79	.01
CT	1,902.07	9	211.34	1.33	-
ST	11,348.04	45	252.18	1.58	-
CST	7,165.93	45	159.24		

System	Mean
Baseline	22.38
Baseline with meters	17.99

TABLE B2.4

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	13,458.13	1	13,458.13	36.23	.01
S	5,428.48	5	1,085.70	2.92	.05
T	1,289.49	9	143.28	.39	-
CS	4,534.22	5	906.84	2.44	.05
CT	2,770.08	9	307.79	.83	-
ST	17,488.00	45	388.84	1.05	-
CST	16,717.96	45	371.51		

System	Mean
Baseline	33.62
Baseline with meters	12.44

TABLE B2.5

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	1,939.72	1	1,939.72	5.83	.05
S	6,522.29	5	1,304.46	3.92	.01
T	3,231.75	9	359.08	1.08	-
CS	1,527.97	5	305.59	.92	-
CT	3,902.22	9	433.58	1.30	-
ST	14,930.15	45	331.78	1.00	-
CST	14,979.36	45	332.87		

System	Mean
Baseline	19.43
Baseline with meters	11.39

TABLE B2.6

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	8,915.16	1	8,915.16	24.36	.01
S	20,110.31	5	4,022.06	10.99	.01
T	3,566.91	9	396.32	1.08	-
CS	16,599.78	5	3,319.96	9.07	.01
CT	2,328.85	9	258.76	.71	-
ST	21,448.50	45	476.63	1.30	-
CST	16,469.37	45	365.99		

System	Mean
Baseline	43.09
Baseline with meters	25.85

TABLE B2.7

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	4.79	1	4.79	.02	-
S	3,421.44	5	684.29	2.82	.05
T	1,887.07	9	209.67	.87	-
CS	4,963.65	5	992.73	4.10	.01
CT	1,764.61	9	196.07	.81	-
ST	16,062.40	45	356.94	1.47	-
CST	10,901.25	45	242.25		

System	Mean
Baseline	16.13
Baseline with meters	16.53

TABLE B2.8

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	9.94	1	9.94	.04	-
S	3,537.18	5	707.44	3.20	.05
T	1,360.78	9	151.20	.68	-
CS	4,192.51	5	838.50	3.79	.01
CT	2,825.43	9	313.94	1.42	-
ST	9,259.64	45	205.77	.93	-
CST	9,949.45	45	221.10		

System	Mean
Baseline	23.23
Baseline with meters	22.66

TABLE B2.9

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	9.24	1	9.24	.07	-
S	788.99	5	157.80	1.16	-
T	632.60	9	70.29	.52	-
CS	877.71	5	175.54	1.29	-
CT	1,060.85	9	117.87	.86	-
ST	6,230.74	45	138.46	1.02	-
CST	6,134.25	45	136.32		

System	Mean
Baseline	23.27
Baseline with meters	22.72

TABLE B2.10

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	556.65	1	556.65	4.06	.05
S	559.47	5	111.89	.82	-
T	1,101.45	9	122.38	.89	-
CS	1,934.82	5	386.96	2.82	.05
CT	1,204.08	9	133.79	.97	-
ST	8,331.62	45	185.15	1.35	-
CST	6,176.49	45	137.26		

System	Mean
Baseline	28.23
Baseline with meters	23.93

TABLE B2.11

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	3,214.71	1	3,214.71	8.01	.01
S	6,939.30	5	1,387.86	3.46	.01
T	4,721.84	9	524.65	1.31	-
CS	4,103.70	5	820.74	2.05	-
CT	4,813.65	9	534.85	1.33	-
ST	21,990.83	45	488.69	1.22	-
CST	18,054.78	45	401.22		

System	Mean
Baseline	39.58
Baseline with meters	29.23

TABLE B2.12

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	23,900.09	1	23,900.09	40.33	.01
S	23,602.04	5	4,720.41	7.97	.01
T	4,525.59	9	502.84	.85	-
CS	15,603.37	5	3,120.67	5.27	.01
CT	2,668.38	9	296.49	.50	-
ST	29,894.71	45	664.33	1.12	-
CST	26,668.05	45	592.62		

System	Mean
Baseline	57.78
Baseline with meters	29.56

TABLE B2.13

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	2,209.09	1	2,209.09	12.31	.01
S	20,426.87	5	4,085.37	22.77	.01
T	2,350.61	9	261.18	1.46	-
CS	3,319.50	5	603.90	3.70	.01
CT	3,308.78	9	367.64	2.05	-
ST	7,886.90	45	175.26	.98	-
CST	8,075.49	45	179.46		

System	Mean
Baseline	19.92
Baseline with meters	28.51

TABLE B2.14

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	1,320.17	1	1,320.17	23.62	.01
S	12,378.52	5	2,475.70	44.29	.01
T	1,028.59	9	114.29	2.04	-
CS	2,319.45	5	463.89	8.30	.01
CT	290.86	9	32.32	.58	-
ST	2,180.83	45	48.46	.87	-
CST	2,515.46	45	55.90		

System	Mean
Baseline	13.56
Baseline with meters	20.20

TABLE B3.1

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	1.13	1	1.13	.11	-
S	834.94	5	166.99	15.73	.01
T	40.19	9	4.47	.42	-
CS	146.95	5	29.39	2.77	.05
CT	49.06	9	5.45	.51	-
ST	440.16	45	9.78	.92	-
CST	477.66	45	10.61		

System	Mean
Baseline	9.55
Baseline with meters	9.56

TABLE B3.2

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	134.37	1	134.37	10.74	.01
S	1,480.97	5	296.20	23.67	.01
T	58.77	9	6.53	.52	-
CS	401.42	5	80.28	6.41	.01
CT	43.97	9	4.89	.39	-
ST	500.23	45	11.12	.89	-
CST	563.23	45	12.52		

System	Mean
Baseline	11.52
Baseline with meters	9.40

TABLE B3.3

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	321.67	1	321.67	2.39	-
S	6,012.33	5	1,202.47	8.94	.01
T	837.19	9	93.02	.69	-
CS	1,876.97	5	375.39	2.79	.05
CT	321.23	9	35.69	.27	-
ST	9,672.60	45	214.95	1.60	-
CST	6,050.95	45	134.47		

System	Mean
Baseline	17.20
Baseline with meters	20.48

TABLE B3.4

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	630.25	1	630.25	5.70	.05
S	2,105.88	5	421.17	3.81	.01
T	694.40	9	77.16	.70	-
CS	563.20	5	112.64	1.02	-
CT	701.62	9	77.96	.71	-
ST	6,453.84	45	143.42	1.30	-
CST	4,972.[illegible]5	45	110.50		

System	Mean
Baseline	13.72
Baseline with meters	18.31

TABLE B4.1

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	4.07	1	4.07	.16	-
S	976.93	5	195.39	7.54	.01
T	387.10	9	43.01	1.66	-
CS	294.42	5	58.88	2.27	-
CT	136.03	9	15.11	.58	-
ST	941.41	45	20.92	.81	-
CST	1,165.60	45	25.90		

System	Mean
Baseline	20.36
Baseline with meters	19.99

TABLE B4.2

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	9.57	1	9.57	.19	-
S	1,210.01	5	242.00	4.77	.01
T	202.77	9	22.53	.44	-
CS	663.31	5	132.66	2.61	.05
CT	675.27	9	75.03	1.48	-
ST	3,137.80	45	69.73	1.37	-
CST	2,284.52	45	50.77		

System	Mean
Baseline	28.79
Baseline with meters	28.23

TABLE B4.3

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	525.67	1	525.67	5.64	.05
S	4,776.80	5	955.36	10.24	.01
T	1,130.71	9	125.63	1.35	-
CS	550.88	5	110.18	1.18	-
CT	550.77	9	61.20	.66	-
ST	3,503.06	45	77.85	.83	-
CST	4,197.60	45	93.28		

System	Mean
Baseline	28.36
Baseline with meters	24.17

TABLE B4.4

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	260.20	1	260.20	2.28	-
S	1,921.57	5	384.31	3.37	.05
T	1,409.59	9	156.62	1.37	-
CS	2,435.88	5	487.18	4.27	.01
CT	1,880.31	9	208.92	1.83	-
ST	5,498.99	45	122.20	1.07	-
CST	5,131.79	45	114.04		

System	Mean
Baseline	26.88
Baseline with meters	29.83

TABLE B4.5

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	603.22	1	603.22	5.05	.05
S	5,450.96	5	1,090.19	9.12	.01
T	767.74	9	85.30	.71	-
CS	823.48	5	164.70	1.38	-
CT	1,241.72	9	137.97	1.15	-
ST	5.176.88	45	115.04	.96	-
CST	5,380.48	45	119.57		

System	Mean
Baseline	32.62
Baseline with meters	28.14

TABLE B4.6

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	3.27	1	3.27	.01	-
S	5,765.19	5	1,153.04	4.29	.01
T	2,566.84	9	285.20	1.06	-
CS	3,874.89	5	774.98	2.88	.05
CT	4,804.39	9	533.82	1.98	-
ST	16,493.78	45	366.53	1.36	-
CST	12,105.61	45	269.01		

System	Mean
Baseline	46.60
Baseline with meters	46.27

TABLE B4.7

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	148.26	1	148.26	1.24	-
S	404.66	5	80.93	.68	-
T	765.51	9	85.06	.71	-
CS	1,438.61	5	287.72	2.41	.05
CT	500.63	9	62.29	.52	-
ST	4,608.43	45	102.41	.86	-
CST	5,366.48	45	119.26		

System	Mean
Baseline	14.13
Baseline with meters	11.90

TABLE B4.8

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	2.68	1	2.68	.01	-
S	3,027.52	5	605.50	2.96	.05
T	851.12	9	94.57	.46	-
CS	1,474.23	5	294.85	1.44	-
CT	3,092.27	9	343.59	1.68	-
ST	9,019.88	45	200.44	.98	-
CST	9,210.10	45	204.67		

System	Mean
Baseline	42.06
Baseline with meters	42.36

TABLE B4.9

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	633.92	1	633.92	8.54	.01
S	5,128.19	5	1,025.64	13.82	.01
T	557.82	9	61.98	.83	-
CS	1,259.68	5	251.94	3.40	.05
CT	430.38	9	47.82	.64	-
ST	2,938.56	45	65.30	.88	-
CST	3,340.46	45	74.23		

System	Mean
Baseline	34.21
Baseline with meters	29.62

TABLE B4.10

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	111.05	1	111.05	2.10	-
S	3,038.80	5	607.76	11.51	.01
T	548.38	9	60.93	1.15	-
CS	695.46	5	139.09	2.63	.05
CT	556.69	9	61.85	1.17	-
ST	3,847.87	45	85.51	1.62	-
CST	2,376.85	45	52.82		

System	Mean
Baseline	26.70
Baseline with meters	28.62

TABLE B4.11

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	1,095.23	1	1,095.23	6.90	.05
S	7,994.24	5	1,598.85	10.07	.01
T	1,660.70	9	184.52	1.16	-
CS	818.91	5	163.78	1.03	-
CT	1,790.27	9	198.92	1.25	-
ST	7,565.56	45	168.12	1.06	-
CST	7,143.97	45	158.75		

System	Mean
Baseline	47.44
Baseline with meters	41.40

TABLE B4.12

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	73.12	1	73.12	.15	-
S	.64	5	1,689.73	3.42	.05
T	.59	9	666.84	1.35	-
CS	.83	5	1,050.97	2.12	-
CT	.23	9	551.91	1.12	-
ST	.26	45	327.78	.66	-
CST	.61	45	494.68		

System	Mean
Baseline	58.75
Baseline with meters	60.31

TABLE B4.13

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	137.77	1	137.77	.10	-
S	111,311.00	5	22,262.20	16.33	.01
T	8,666.03	9	962.89	.71	-
CS	5,531.05	5	1,106.21	.81	-
CT	12,743.13	9	1,415.90	1.04	-
ST	65,528.46	45	1,456.19	1.07	-
CST	61,351.39	45	1,363.36		

System	Mean
Baseline	77.47
Baseline with meters	75.33

TABLE B4.14

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	1,106.44	1	1,106.44	.73	-
S	52,265.17	5	10,453.03	6.90	.01
T	19,116.08	9	2,124.01	1.40	-
CS	6,876.64	5	1,375.33	.91	-
CT	11,552.05	9	1,283.56	.85	-
ST	42,156.57	45	936.81	.62	-
CST	68,213.42	45	1,515.85		

System	Mean
Baseline	57.07
Baseline with meters	51.00

TABLE B5.1

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	40.80	1	40.80	2.11	-
S	1,646.35	5	329.27	17.00	.01
T	509.86	9	56.65	2.93	.01
CS	307.37	5	61.47	3.17	.05
CT	111.12	9	12.35	.64	-
ST	1,158.41	45	25.74	1.33	-
CST	871.51	45	19.37		

System	Mean
Baseline	13.82
Baseline with meters	12.65

TABLE B5.2

Souce of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	98.17	1	98.17	3.91	-
S	1,171.27	5	234.25	9.32	.01
T	162.56	9	18.06	.72	-
CS	128.79	5	25.76	1.03	-
CT	194.51	9	21.61	.86	-
ST	1,157.77	45	25.73	1.02	-
CST	1,130.46	45	25.12		

System	Mean
Baseline	13.30
Baseline with meters	11.49

TABLE B5.3

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	3,483.86	1	3,483.86	20.66	.01
S	2,601.71	5	520.34	3.09	.05
T	1,719.62	9	191.07	4.22	.01
CS	639.57	5	127.91	.76	-
CT	1,321.83	9	146.87	.87	-
ST	3,832.50	45	85.17	.51	-
CST	7,586.92	45	168.60		

System	Mean
Baseline	40.36
Baseline with meters	29.58

TABLE B5.4

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	5,629.05	1	5,629.05	15.08	.01
S	10,821.65	5	2,164.33	5.80	.01
T	7,493.32	9	832.59	2.23	.05
CS	3,131.88	5	626.38	1.68	-
CT	1,423.92	9	158.21	.42	-
ST	18,393.73	45	408.75	1.09	-
CST	16,800.03	45	373.33		

System	Mean
Baseline	51.70
Baseline with meters	38.01

TABLE B5.5

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	2,698.63	1	2,698.63	7.53	.01
S	16,113.68	5	3,222.74	9.00	.01
T	2,722.20	9	302.47	.84	-
CS	5,395.76	5	1,079.15	3.01	.05
CT	2,417.75	9	268.64	.75	-
ST	17,074.87	45	379.44	1.06	-
CST	16,131.40	45	358.47		

System	Mean
Baseline	89.05
Baseline with meters	79.56

TABLE B5.6

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	779.37	1	779.37	12.66	.01
S	11[illegible]7.35	5	2,361.47	38.35	.01
T	1,[illegible]6.36	9	111.82	1.82	-
CS	491.81	5	98.36	1.60	-
CT	351.87	9	39.10	.63	-
ST	3,917.75	45	87.06	1.41	-
CST	2,770.98	45	61.58		

System	Mean
Baseline	11.03
Baseline with meters	5.93

TABLE B5.7

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	1,005.69	1	1,005.69	6.48	.01
S	8,457.26	5	1,691.45	10.90	.01
T	3,538.75	9	393.19	2.53	.05
CS	748.40	5	149.68	.96	-
CT	1,830.74	9	203.42	1.31	-
ST	8,657.56	45	192.39	1.24	-
CST	6,981.69	45	155.15		

System	Mean
Baseline	10.05
Baseline with meters	4.26

TABLE B5.8

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	779.93	1	779.93	10.08	.01
S	2,519.52	5	503.90	6.51	.01
T	128.86	9	14.32	.18	-
CS	1,235.27	5	247.05	3.19	.05
CT	438.54	9	48.73	.63	-
ST	2,675.09	45	59.45	.77	-
CST	3,483.42	45	77.41		

System	Mean
Baseline	6.43
Baseline with meters	1.33

TABLE B5.9

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	528.04	1	528.04	6.08	.05
S	617.35	5	123.47	1.42	-
T	992.26	9	110.25	1.27	-
CS	345.47	5	69.09	.80	-
CT	884.18	9	98.24	1.13	-
ST	2,586.91	45	57.49	.66	-
CST	3,910.02	45	86.89		

System	Mean
Baseline	16.99
Baseline with meters	12.80

TABLE B5.10

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	364.22	1	364.22	8.95	.01
S	2,018.12	5	403.62	9.91	.01
T	979.79	9	.87	2.67	.05
CS	249.53	5	.91	1.23	-
CT	695.44	9	.27	1.90	-
ST	1,890.96	45	.02	1.03	-
CST	1,832.06	45	.71		

System	Mean
Baseline	18.66
Baseline with meters	15.17

TABLE B5.11

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	4,677.63	1	4,677.63	12.05	.01
S	17,828.42	5	3,565.68	9.18	.01
C	2,752.50	9	305.87	.79	-
CS	5,919.40	5	1,183.88	3.05	.05
CT	2,303.65	9	255.96	.66	-
ST	18,147.07	45	403.27	1.04	-
CST	17,474.60	45	388.32		

System	Mean
Baseline	86.07
Baseline with meters	73.58

TABLE B5.12

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	5.407.86	1	5,407.86	16.28	.01
S	18,722 [illegible]	5	3,744.50	11.27	.01
T	4,22[illegible]	9	469.97	1.41	-
CS	3,003.87	5	600.77	1.81	-
CT	1,242.71	9	138.00	.42	-
ST	16,14[illegible].44	45	358.74	1.08	
CST	.64	45	332.26		

System	Mean
Baseline	31.17
Baseline with meters	17.74

TABLE B5.13

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	309.19	1	309.19	1.57	-
S	18,382.36	5	3,676.47	18.61	.01
T	2,114.34	9	234.93	1.19	-
CS	6,535.36	5	1,307.07	6.62	.01
CT	849.37	9	94.37	.48	-
ST	13,974.62	45	310.55	1.57	-
CST	8,388.12	45	197.51		

System	Mean
Baseline	28.73
Baseline with meters	31.94

TABLE B5.14

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
C	212.75	1	212.75	50.37	.01
S	581.92	5	116.38	27.83	.01
T	27.85	9	3.09	.74	-
CS	56.09	5	11.22	2.68	.05
CT	39.19	9	4.35	1.04	-
ST	250.16	45	5.56	1.33	-
CST	188.18	45	4.18		

System	Mean
Baseline	6.77
Baseline with meters	9.43

TABLE B5.16

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	P
Tk	137,483.41	3	45,827.80	93.93	.01
S	10,896.60	5	2.179.37	4.47	.05
T	6,306.56	19	331.92	.68	-
TkS	59,076.41	15	3,938.43	8.07	-
TkT	29,602.88	57	519.35	1.06	-
ST	[illegible].091.61	95	622.02	1 36	-
TkST	13,950.22	285	487.90		

TABLE B6.1

Trials	Force
1	49.23
2	51.02
3	57.82
4	49.51
5	58.84
6	53.50
7	50.88
8	50.34
9	46.38
10	54.68
11	57.17
12	49.53
13	46.25
14	50.29
15	57.30
16	49.06
17	50.62
18	53.59
19	55.49
20	51.23

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2. GOVT ACCESSION NO.:
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): OPERATOR PERFORMANCE IN UNDERSEA MANIPULATOR SYSTEMS: STUDIES OF CONTROL PERFORMANCE WITH VISUAL FORCE FEEDBACK.
5. TYPE OF REPORT & PERIOD COVERED: Final Report. Jan. 1974 – Jan. 1977.
6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): W. R. Bertsche, A. J. Pesch, C. L. Winget, K. P. Logan
8. CONTRACT OR GRANT NUMBER(s): N00014-74-C-0179
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Woods Hole Oceanographic Institution, Woods Hole, MA and Eclectech Associates, Inc., North Stonington, CT 06359
10. PROGRAM ELEMENT PROJECT, TASK AREA & WORK UNIT NUMBERS: NR 196-131
11. CONTROLLING OFFICE NAME AND ADDRESS: Engineering Psychology Programs, Code 455, Office of Naval Research, Arlington, VA 22217
12. REPORT DATE: January 1977
13. NUMBER OF PAGES: 118
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): 137p.
15. SECURITY CLASS (of this report): Unclassified

15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Unclassified - Distribution of this document is unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

1. Man/Machine Interface
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3. Manipulator Response Variables
4. Undersea Manipulators
5. Servo Control
6. Human Performance

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The study was conducted to identify and evaluate selected design variables in undersea manipulator systems with force feedback capability.

The objective was to develop relationships between selected force feedback variables and operator control performance. A comprehensive series of engineering tests which describe response characteristics of the experimental manipulator system were completed. (Cont. on back)

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